Posthurricane Survey of Experimental Dunes on Padre Island, Texas

by

B.E. Dahl, P.C. Cotter, D.B. Wester, and D.D. Drbal

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This report summarizes the impact of Hurricane Allen (August 1980) on dune configuration, sand accretion or erosion,and changes in the vegetation on north Padre Island. Four experimental foredunes, the result of grass plantings from 1969 to 1973, and an unplanted control section were monitored in 1975-1977 and also in 1981. The 1981 posthurricane data were compared where possible, with the previous studies. Foredune elevation surveys were completed in March 1981; accompanying vegetation transects were made in July 1981.

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Hurricane Allen caused erosion of the dune face of all the experimental dunes, but caused a breach in only one dune. The beach elevations had returned to approximately prehurricane heights by the time the area was resurveyed. The unplanted control dune provided little resistance to waves generated by the storm and a large quantity of sand was deposited inland.

During the past 5 years the experimental dunes have accumulated sand at an annual rate of 11.5 cubic meters per meter of beach compared with 9.3 cubic meters per meter of beach for the unplanted control area. The higher annual accumulation rate on the experimental dunes is due to the greater abundance of vegetation.

Vegetation on the experimental dunes apparently continues to spread seaward at 1.5 to 1.8 meters per year. The total dune width has expanded 1.8 to 2.4 meters annually since 1976. There has been little invasion of other species into the sea oats (*Uniola paniculata*) and bitter panicum (*Panicum amarum*) plantings, even after 8 to 10 years. Landward ground cover of the unplanted control dune decreased from 28 percent in 1976 to 17 percent in 1981 due to sand deposition on existing vegetation. Landward ground cover of experimental dunes increased from 39 percent in 1976 to 56 percent in 1981, because the foredune protected vegetation from storm waves and sand deposition. Also, freshwater ponded behind the foredunes, creating a favorable habitat for vegetation. The less salt-tolerant plants also benefited from the decreased salt spray landward of the experimental foredunes.

Vegetation on the backshore was eliminated during the storm, but rapidly is becoming reestablished from residual perennial grass roots and rhizomes. Foredunes on Padre Island dissipate hurricane-generated waves, thus lessening water damage to the mainland; they are also major sand reservoirs, thereby helping hold newly deposited sand. A large, midisland, unvegetated dune field has migrated landward 27 meters per year since 1973.

PREFACE

This report contains results of a study to monitor effectiveness of experimental foredunes to provide coastal protection from a major hurricane, in this case, Hurricane Allen which impacted Padre Island in August 1980. Dunes evaluated resulted from grass plantings made from 1969 to 1973; these were compared to an unplanted beach segment. Parameters measured included rates and regions of sand deposition, beach erosion, and vegetation dynamics. Rate of plant succession occurring on an inner island active dune field was also evaluated. Results of this and earlier publications (Dahl, et al., 1975; Dahl and Goen, 1977) should provide coastal zone managers with procedures for constructing barriers that can effectively protect coastal populations against storm surges as well as improve environmental quality. Especially valuable to natural resource managers, environmentalists, and naturalists would be the minimum disruption to the ecosystem entailed by these methods. The original research was carried out under the U.S. Army Coastal Engineering Research Center's (CERC) Foredune Ecology work unit, Environmental Impact Program, Environmental Quality Area of Civil Works Research and Development, and the evaluation was conducted under contract with the National Park Service.

This report was prepared by Bill E. Dahl, Paul F. Cotter, David B. Wester, and Doug D. Drbal, professor and research assistants, respectively, Department of Range and Wildlife, Texas Tech University (TTU), Lubbock. Dr. K. Yarborough, National Park Service, Santa Fe, New Mexico, was the contracting officer's representative.

The authors appreciate the help, advice, facilities, and encouragement of personnel of the Padre Island National Seashore and Welder Wildlife Foundation, Sinton, Texas. P. Knutson provided advice and assistance during the course of this and earlier projects. Special thanks are due J. Cone, S. Jarrett, T. Mills, J.S. Pitts, G. Scott, R. Steed, G. Tanner, and S. Wesley for help in fieldwork, data analysis, and preparation of the final manuscript. Dr. C. Britton was especially helpful with the contract photography needs.

P.L. Knutson was contract monitor for the report, under the general supervision of E.J. Pullen, Chief, Coastal Ecology Branch, and Mr. R.P. Savage, Chief, Research Division, CERC.

Technical Director of CERC was Dr. Robert W. Whalin, P.E.

Comments on this publication are invited.

Approved for publication in accordance with Public Law 166, 79th Congress, approved 31 July 1945, as supplemented by Public Law 172, 88th Congress, approved 7 November 1963.

Ted E. Bishop

TED E. BISHOP
Colonel, Corps of Engineers
Commander and Director

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CONVERSION FACTORS, U.S. CUSTOMARY TO METRIC (SI) UNITS OF MEASUREMENT

U.S. customary units of measurement used in this report can be converted to metric (SI) units as follows:

Multiply	by	To obtain
inches	25.4	millimeters
	2.54	centimeters
square inches	6.452	square centimeters
cubic inches	16.39	cubic centimeters
feet	30.48	centimeters
	0.3048	meters
square feet	0.0929	square meters
cubic feet	0.0283	cubic meters
yards	0.9144	meters
square yards	0.836	square meters
cubic yards	0.7646	cubic meters
miles	1.6093	kilometers
square miles	259.0	hectares
knots	1.852	kilometers per hour
acres	0.4047	hectares
foot-pounds	1.3558	newton meters
millibars	1.0197×10^{-3}	kilograms per square centimeter
ounces	28.35	grams
pounds	453.6	grams
	0.4536	kilograms
ton, long	1.0160	metric tons
ton, short	0.9072	metric tons
degrees (angle)	0.01745	radians
Fahrenheit degrees	5/9	Celsius degrees or Kelvins[1]

[1] To obtain Celsius (C) temperature readings from Fahrenheit (F) readings, use formula: C = (5/9) (F -32).

To obtain Kelvin (K) readings, use formula: K = (5/9) (F -32) + 273.15.

POSTHURRICANE SURVEY OF EXPERIMENTAL DUNES ON

PADRE ISLAND, TEXAS

by

B.E. Dahl, P.C. Cotter, D.B. Wester, and D.D. Drbal

I. INTRODUCTION

Flood damage from hurricanes is a major concern to inhabitants of the Texas gulf coast. Barrier islands, such as Padre Island, provide significant protection against high water through the damming effect of foredunes, which form parallel to the beach. Where these foredunes have eroded, storm surges transport sand inland from the beach onto lowland vegetation and into lagoons, where it accumulates on roads and in navigational channels adjacent to the islands. After the severe flooding from Hurricane Carla in 1961, the mainland residents requested restoration of these natural dunes on Padre Island.

From 1968 to 1974 the U.S. Army Coastal Engineering Research Center (CERC) supported research to define propagation and transplanting techniques with beach grass to construct and rehabilitate these coastal foredunes (Dahl, et al., 1975). The data collected included information on changes in dune dimensions and beach topography, encroachment of indigenous flora, and comparisons with naturally occurring foredunes. During these studies, several foredunes were shaped from test plantings on the north and south ends of Padre Island (Fig. 1). On completion of the initial contracts, CERC continued monitoring the foredunes formed from the beach-grass plantings on north Padre Island beaches in 1975 and 1976 to evaluate the long-term performance and effects of the foredunes (Dahl and Goen, 1977).

Hurricane Anita struck the coast of northern Mexico in August 1977, causing substantial foredune erosion on south Padre Island. The storm caused significant reorientation of sand even on north Padre Island beaches, but it did not damage the experimental foredunes of north Padre Island. This was the only major storm affecting Padre Island beaches since the original test plantings were made from 1969 to 1973 and the cross-sectional profiles were resurveyed in September 1977. On 9 and 10 August 1980, Hurricane Allen violently struck the Texas coast, entering the mainland between the Mansfield Channel and Kingsville (Fig. 1). South Padre Island, which has lower elevations than north Padre Island, was dramatically altered with frequent overwash channels. The storm substantially damaged the Padre Island National Seashore Malaquite Beach facilities on north Padre Island, significantly altering beach vegetation and eroding the beach face of foredunes, with the hurricane-generated waves breaching the island's dunes in many instances. This report summarizes the impact of Hurricane Allen on the dune configuration, sand yardage accretion or erosion, and changes in the vegetation on four experimental foredune sections and one unplanted section within the boundaries of the Padre Island National Seashore. This was accomplished by comparing the 1981 posthurricane surveys with those of 1975-77.

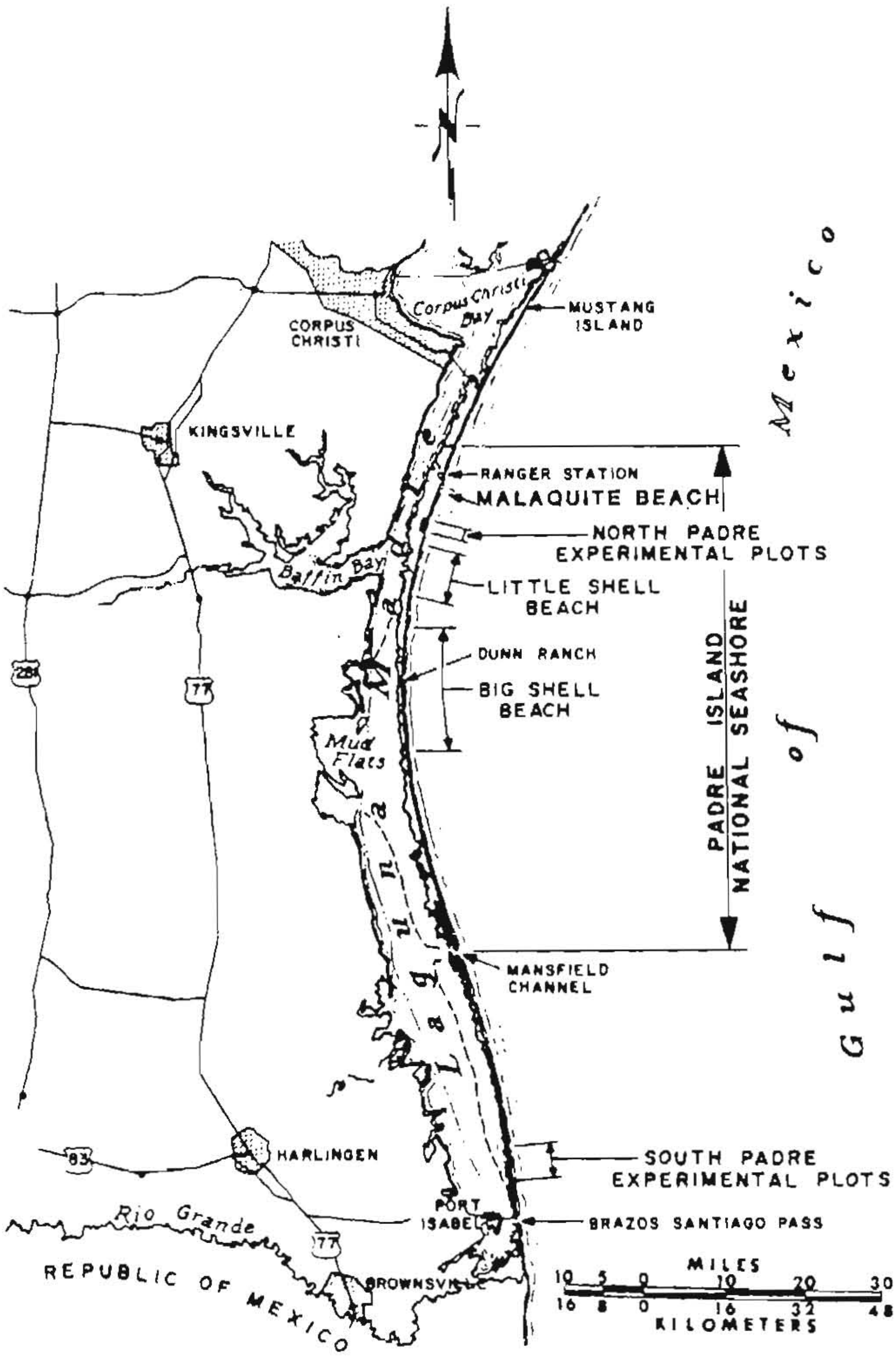


Figure 1. Map of Padre Island, Texas.

II. STUDY AREA

Padre Island has a subtropical, semiarid climate, moderated by maritime tropical air from the Gulf of Mexico. The summer months are hot, with little daily or weekly variation. Winter (December to February) is mild with wide fluctuations in temperature; freezing temperatures are infrequent. Precipitation is irregular, both monthly and annually, with no sharply defined seasons. Within the last century, the annual precipitation at Corpus Christi, the nearest station with long-time weather data, has ranged from 1222 millimeters in 1888 to 136 millimeters in 1917, with an average of 678 millimeters. Excessive precipitation associated with hurricanes, usually in late summer and early fall, biases the annual average precipitation upward. Without the hurricanes, the annual average would be lower and more indicative of the stress associated with semiarid lands where droughts are frequent but irregular (Carr, 1966). The average temperature for Corpus Christi is 21.7° Celsius (Department of Commerce, 1970).

Two principal wind regimes dominate the Texas coastal zone--persistent southeasterly winds from March to September and north-northeasterly winds from October to February (Behrens, Watson, and Mason, 1977). However, prevailing winds (disregarding windspeed) are onshore 11 months of the year (Dahl, et al., 1975). Northerly winds are associated with frontal passages and are usually strong with concurrent precipitation. However, some northers are dry, creating small dunes along the beach with each passage. Prevailing winds then transport this sand back to the foredunes.

The coastal topography of the mainland adjacent to Padre Island is relatively flat with soils developed from Pleistocene and recent unconsolidated clastic sediments. The soils of Padre Island developed on recent marine and eolian soils (Brown, et al., 1976). The sand particle size is predominantly fine to very fine. Soils vary in salt content and in amounts of shell and organic matter. The highest organic matter content from beach sands was 0.1 percent. Shell fragments were generally less than 1 percent (Dahl, et al., 1975).

A schematic cross-sectional profile of north Padre Island and the dominant plants of major communities are in Figure 2. North Padre Island is predominantly a grassland of midheight. Seacoast bluestem (*Schizachyrium scoparium* var. *littoralis*), seashore dropseed (*Sporobolus virginicus*), gulfdune paspalum (*Paspalum monostachyum*), and saltmeadow cordgrass (*Spartina patens*) are species that commonly occur from the foredune across the island.

The number of species on the shoreface of the dunes is limited, with sea oats (*Uniola paniculata*) the dominant sand-trapping plant. Other species capable of trapping or binding sand are saltmeadow cordgrass, seashore dropseed, bitter panicum (*Panicum amarum*), railroad vine (*Ipomoea pes-Caprae*), and gulf croton (*Croton punctatus*). After dunes have been started by pioneer vegetation, forbs such as beach groundcherry (*Physalis viscosa*), beach evening primrose (*Oenothera drummondii*), and prairie senna (*Cassia fasciculata*) often become common.

Of particular interest to this study is the vegetation of the backshore and the foredune foreslope, and the natural succession of plants from a barren, hurricane-planed backshore to a continuous, mature foredune ridge. Sea purslane (*Sesuvium portulacastrum*), one of the first species to reappear

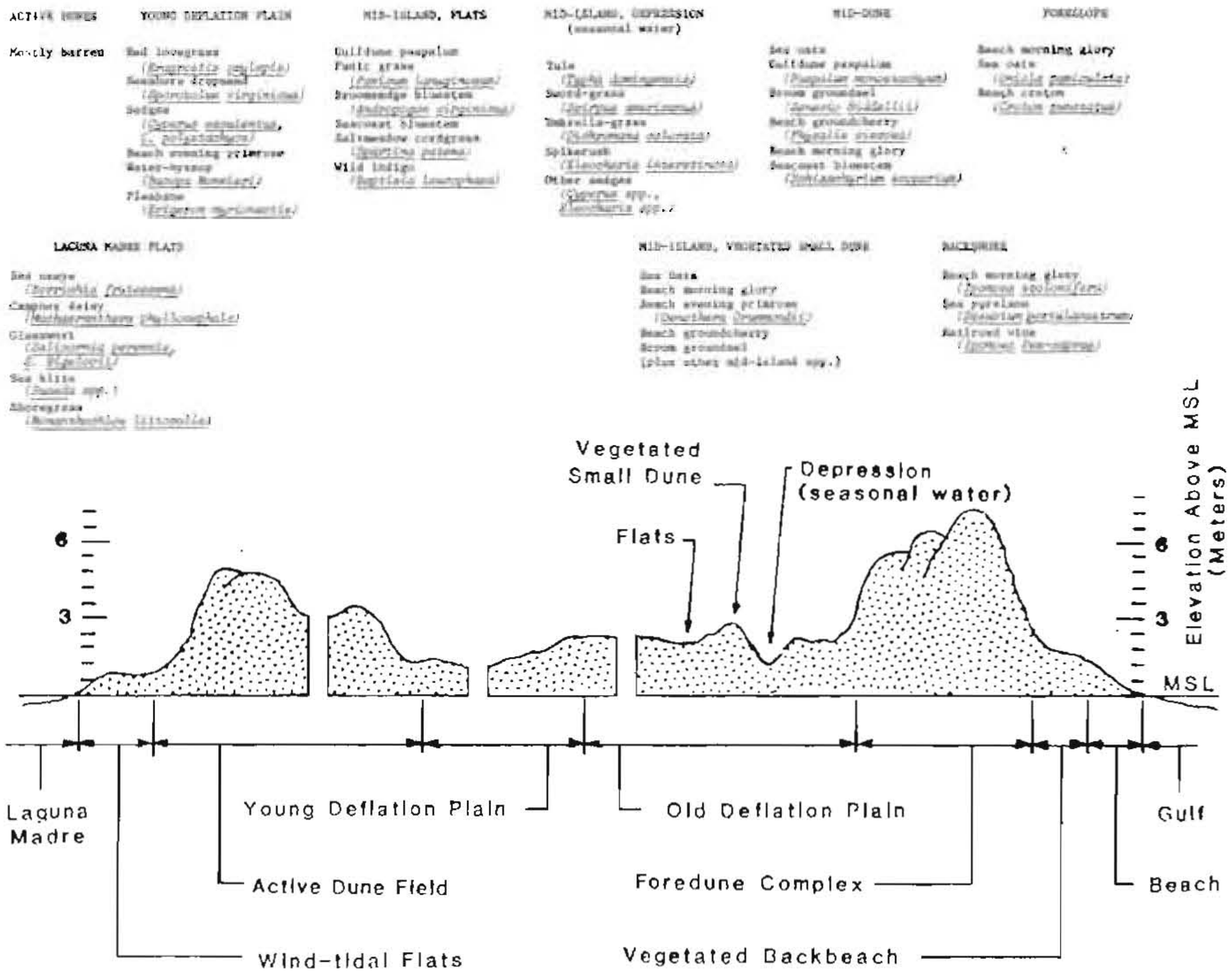


Figure 2. Schematic cross-sectional profile of north Padre Island and some dominant plants of major communities (vicinity of Ranger Station, Padre Island National Seashore).

on the denuded backshore, is vegetatively dispersed by wave and wind action. Clumps of sea purslane trap sand, forming small dunes that rise only slightly above the beach surface. Beach morning glory (*Ipomoea stolonifera*), railroad vine, gulf croton, sea oats, saltmeadow cordgrass, bitter panicum, and seashore dropseed are early colonizers (Dahl, et al., 1975).

Rhizomatic growth and tillering of these plants, especially sea oats and bitter panicum, are stimulated by the accumulation of fresh sand continually blown onshore. Eolian sand is trapped by exposed grass blades and it eventually becomes stabilized by the grass roots and rhizomes. Nourished by fresh beach sand blowing inland, the unconnected hummock dunes of sea oats, bitter panicum, saltmeadow cordgrass, and seashore dropseed continue growing and eventually interconnect, forming a dune ridge (Fig. 3). New hummock dunes begin forming shoreward, and in this manner, the foredune grows toward the gulf. This shoreward growth eventually eliminates fresh sand accumulation on the rear of the dune ridge, and gives additional protection from wind and salt spray. The less salt-tolerant species and those not adapted to growing in accumulating sand then become established, e.g., seacoast bluestem, gulfdune paspalum, broom groundsel (*Senecio riddellii*), and beach groundcherry (Dahl, et al., 1975).

The time scale for these sequences depends on the intervals between storms, the severity of previous storm damage, the proximity of undamaged colonizing species, and the precipitation cycle. The area containing the present study plots was barren in 1937, but a vegetated foredune ridge had appeared with a vegetated plain to the west by 1948. After Hurricanes Carla and Beulah in 1967, the dune ridge was absent, and the area was again barren with a field of active sand dunes migrating west.

III. METHODS AND PROCEDURES

1. Elevation Surveys of Experimental Dunes.

A summary of the five experimental dune areas evaluated in this report is in Table 1, which corresponds with the study-site map in Figure 4. The exact location of these areas referenced to two surveyed base lines (east and west) is in Appendix A. Elevational profile surveys for the five areas (one unplanted control and four planted) were conducted in March 1975, August 1975, March 1976, August 1976, September 1977, and March 1981.

a. Foredune Profiles. Cross-sectional profiles were made in each of the five experimental dunes. Elevations were taken at 3-meter intervals (rod readings to the nearest 0.003 meter). Profiles were made in the following locations:

(1) Unplanted control dune - eight profiles, 30 meters apart, from 30 meters seaward of the natural dune area to 61 meters across the foredune.

(2) Planted dunes - 30 meters seaward of the grass extension of the dune to 58 meters across the dune.

(a) 366-meter sea oats dune - 12 profiles, 30 meters apart.

Figure 3. New dune ridge forming naturally on the unplanted control area, a site without a natural dune similar to the planted dune sites. It has been monitored since 1975.

Table 1. Control and experimental planting sites on north Padre Island.

Description	Planting dates	Comments
Unplanted control dune	not planted	Monitored since 1974.
366-meter sea oats	Mar. 1969	Original plantings--three-fourths saltmeadow cordgrass and one-fourth sea oats. Survival--cordgrass, 14 percent; sea oats, 46 percent. Cattle grazing an early problem. Supplemental fill-in plantings of sea oats, cordgrass, and panicum (shoredune and bitter).
Dune-width extension. Planted seaward of the south end of monthly plantings.	Apr. 1973	Mixture of 3:1 bitter panicum to sea oats. Survival--panicum, 62 percent; sea oats, 1 percent.
335-meter bitter panicum	Feb. 1970	Bitter panicum alternated with sea oats seed. Survival--panicum, 17 percent; sea oats, unsuccessful. Subsequent patchwork planting.
366-meter bitter panicum	Feb. 1972 and Apr. 1972	North half planted with bitter panicum--76 percent survival. South half planted with sea oats, which were later destroyed by jackrabbits. Replanted in April with bitter panicum--17-percent survival.

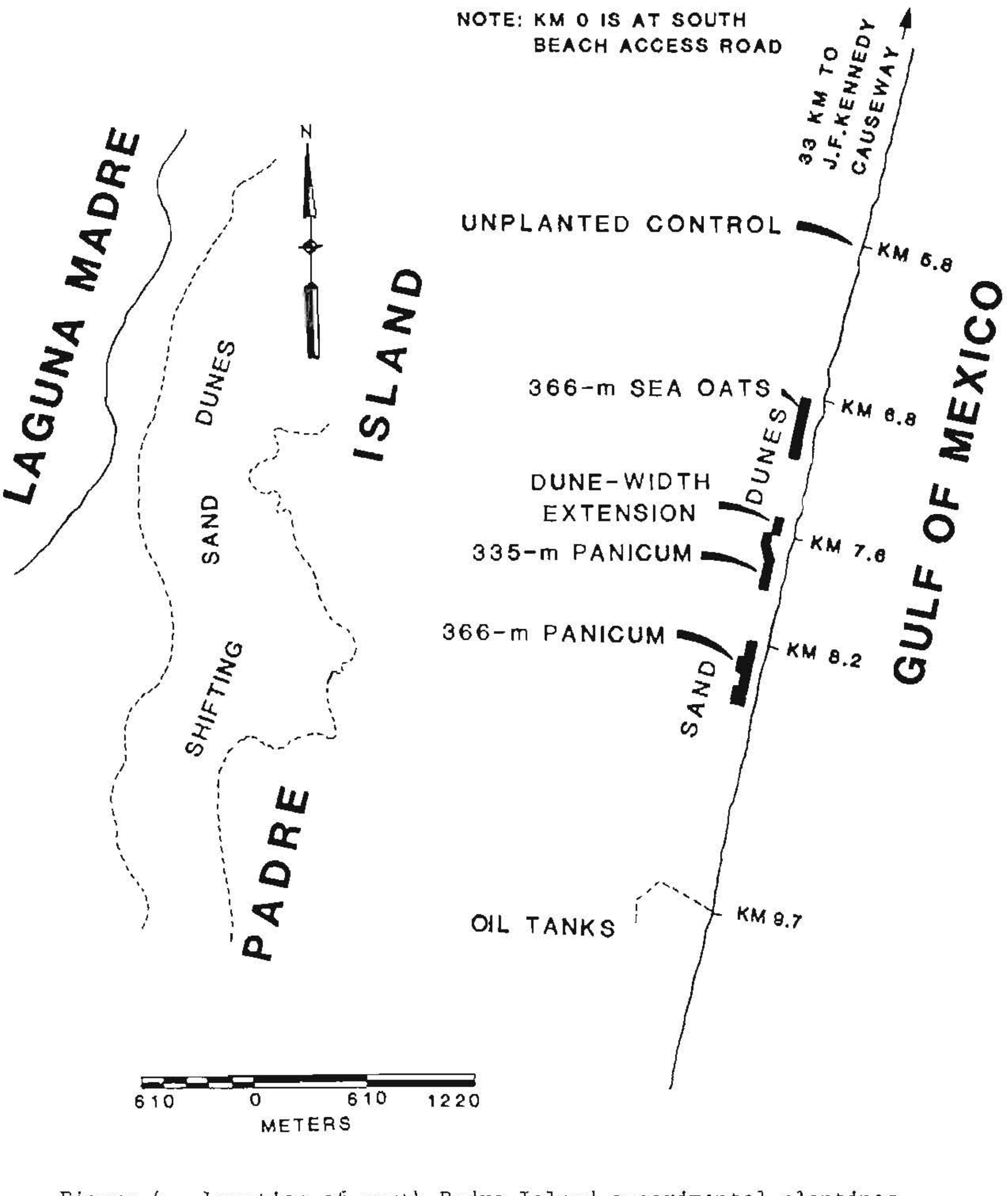


Figure 4. Location of north Padre Island experimental plantings.

(b) Dune-width extension - one profile.

(c) 335-meter bitter panicum dune - 12 profiles, 27 meters apart.

(d) 366-meter bitter panicum dune - 12 profiles, 30 meters apart.

b. Beach Profiles. Cross-sectional profile surveys were made in each of the experimental areas from the mean sea level (MSL) landward to the east base line. Beach profile elevations were read at 6-meter intervals. Profiles were made in the following locations:

(1) Unplanted control area - two profiles 91 meters apart.

(2) Planted dune areas.

(a) 366-meter sea oats dune - two profiles 122 meters apart.

(b) Dune-width extension dune - one profile.

(c) 335-meter bitter panicum dune - two profiles 110 meters apart.

(d) 366-meter bitter panicum dune - two profiles 91 meters apart.

c. Longitudinal Profiles. In 1975-76 two longitudinal surveys were made along the top of the dune and parallel with the beach for the 366-meter sea oats, 335-meter bitter panicum, and 366-meter bitter panicum dunes. One profile line was placed to coincide with the seaward crest of the foredunes. The other was 9 to 15 meters landward of the first profile line. In 1981 the second profile was omitted. Also, in 1981, a longitudinal profile was surveyed for the first time on the newly shaping dune in the unplanted natural area. For the dune-width extension dune, longitudinal profiles were surveyed for both the seaward 15-meter width and the landward 15-meter width. Elevations were recorded with each abrupt change in topography. Distances were measured by tape to the nearest 0.3 meter.

2. Elevational Surveys of Naturally Formed Dunes.

Four cross-sectional profile surveys of existing naturally formed dunes were resurveyed in March 1981. These were:

(a) One cross section about 91 meters north of the Ranger Station access road. This dune was first surveyed in 1974.

(b) Three cross sections designated as (1) Pedtraf 18 meters south; (2) Pedtraf 2.2 kilometers south; and (3) Pedtraf 2.6 kilometers south.

These were surveyed on 3 August 1980 just prior to Hurricane Allen by Chaney, Williges, and Taylor (1980). The latter three surveys began at the crest of the foredune and continued to the shoreline on the beach. Because the latter surveys were not referenced to MSL, the crest elevations with respect to MSL of the March 1981 survey were used to estimate the crest elevations of the August 1980 survey. With this approximation the beach elevation (where the surveys were terminated) was determined to be approximately 0.6 meter below MSL.

3. Vegetation.

In August 1975, August 1976, and July 1981 vegetation transects were made in the five experimental dune areas. The following transects were placed paralleling the beach: a 60-plot transect on the seaward slope of the foredune, a 60-plot transect on the landward slope of the foredune, a 40-plot transect 8 meters landward of the dune, a 40-plot transect 38 meters landward of the dune, and a 40-plot transect 69 meters landward of the dune. A 133-centimeter-diameter circular plot with an area of 1 square meter was used. Frequency and cover data were recorded in each plot (App. B). Cover classes recorded were: 1, 0 to 1 percent; 2, 1 to 5 percent; 3, 5 to 25 percent; 4, 25 to 50 percent; 5, 50 to 75 percent; 6, 75 to 90 percent; 7, 95 to 99 percent; and 8, 99 to 100 percent. An importance value (IV) was computed by multiplying cover times frequency.

IV. RESULTS

Hurricane Allen's effect on north Padre Island's foredunes built from the 1969 to 1973 test plantings was less severe than expected. The storm caused erosion of the seaward face of the dunes (including the naturally formed ones) leaving a nearly vertical face, but it breached only one dune (the 335-meter bitter panicum dune) (Fig. 5). A second hurricane impact was the total destruction of the hummock dunes that had formed seaward of the experimental foredunes (Fig. 6). Even major accumulations of sand due to vegetation growing on a 6.5-kilometer segment of the beach reserved for pedestrians were removed during the storm (Fig. 7). These were the more obvious hurricane impacts. However, a comprehensive understanding of the beach and dune system and its response to severe coastal storms can be gained from an analysis of the long-term data available on this area. This report deals mainly with the beach and dune changes over time, mostly during the past 6 years, and particularly as affected by Hurricane Anita in 1977 and Hurricane Allen in 1980.

1. Sand Volume.

a. Mean Sea Level Inland 200 Meters. From the Padre Island surveys, sand volumes were computed several ways to show the dynamics of the sand accumulation and redistribution. First, consider the total sand volume from MSL inland through that part of the beach normally occupied by the foredunes. A 200-meter segment was used; the seaward side, 108 meters was designated the beach segment, and a 108- to 200-meter segment was designated the foredune segment (Table 2; Figs. 8 to 12). Because the March 1981 surveys were made about 7 months after Hurricane Allen, only the 335-meter bitter panicum dune, which was breached during the storm, showed a net loss of sand. Therefore, for a hypothesis as to what actually occurs on a beach during a hurricane, the

Figure 5. (Top) The seaward face of 366-meter bitter panicum dune (11 Sept. 1980) following Hurricane Allen. (Bottom) Breach (46 meters) in the 335-meter bitter panicum dune created by Hurricane Allen.

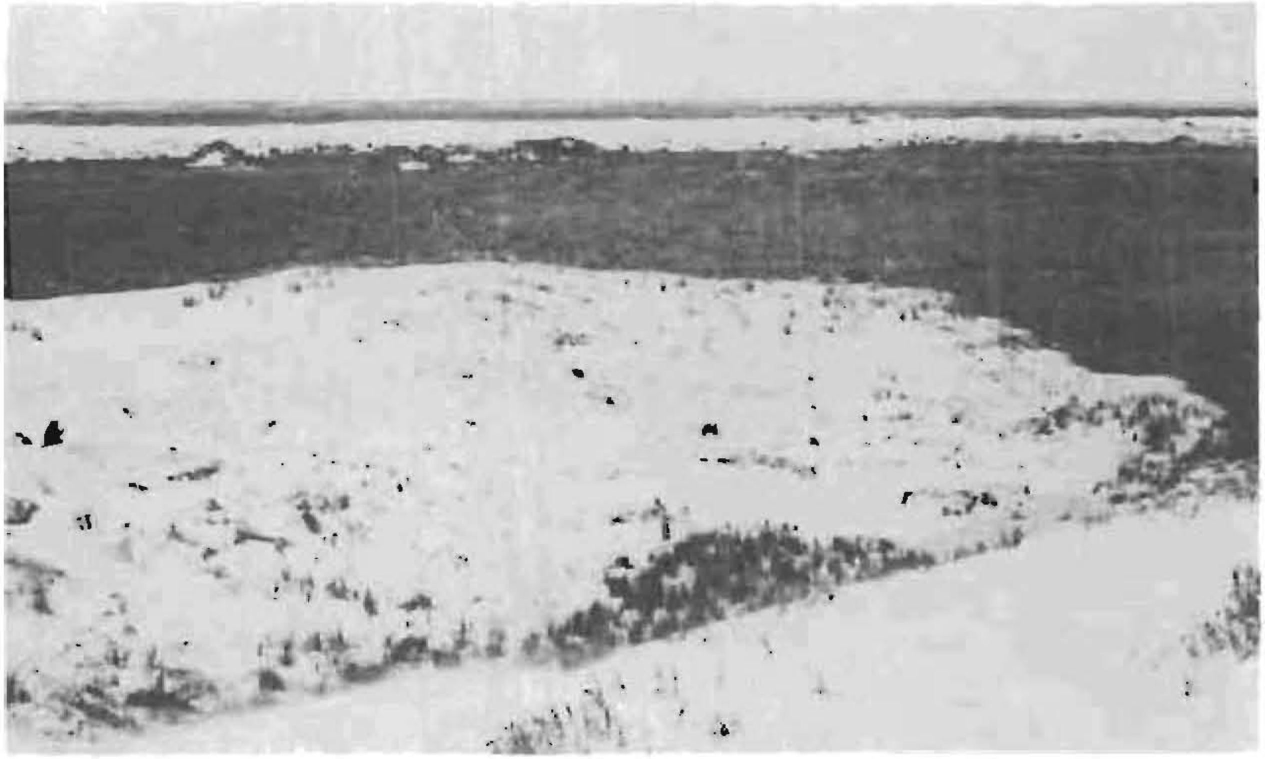


Figure 6. (Top) Sand carried by hurricane waves between or through breached dunes and deposited on inland vegetation. (Bottom) Hummock dunes growing in front of the study dunes, which were later removed by Hurricane Allen.

Figure 7. (Top) Beach vegetation on pedestrian beach in May 1980. (Bottom) Pedestrian segment of the beach after Hurricane Allen in August 1980.

Table 2. Total sand volume for beach and foredune cross sections of five study dunes.

Location	Volume by survey date (m³/m)					
STUDY DUNES	Mar. 1975	Aug. 1975	Mar. 1976	Aug. 1976	Sept. 1977	Mar. 1981
Beach segment (MSL to 108 meters)						
Unplanted area	100.6	124.4	120.7	121.4	97.6	122.5
366-meter sea oats	100.6	123.4	112.9	116.4	94.0	115.1
Dune-width extension	[1]	120.4	118.4	129.4	78.0	129.8
335-meter bitter panicum	100.8	112.1	114.1	119.9	83.2	118.4
366-meter bitter panicum	91.6	106.6	115.1	111.1	87.8	126.4
Avg.	98.4	117.4	116.2	119.6	88.1	122.4
Foredune segment (108 meters to 200 meters)						
Unplanted area	201.7	204.2	211.2	210.7	214.6	240.9
366-meter sea oats	219.7	229.5	233.5	237.0	242.5	264.2
Dune-width extension	[1]	227.0	224.0	245.6	255.6	296.6
335-meter bitter panicum	203.4	207.9	215.5	222.7	246.8	233.2[2]
366-meter bitter panicum	207.4	211.7	209.7	224.8	223.4	251.4
Avg.	208.1	216.1	218.8	228.2	236.6	257.3
Total segment (MSL to 200 meters)						
Unplanted area	302.3	328.6	331.9	332.1	312.1	363.4
366-meter sea oats	320.3	352.9	346.4	353.4	336.5	379.3
Dune-width extension	323.8[1]	347.4	342.4	375.0	333.6	426.3
335-meter bitter panicum	304.3	320.3	329.6	342.6	330.1	351.6
366-meter bitter panicum	299.0	318.3	324.8	335.9	311.2	377.8
Avg.	309.9	333.5	335.1	347.8	324.7	379.7

[1] Estimated not surveyed in March 1975.

[2] This apparent sand loss occurred because this dune was breached by Hurricane Allen and one of the two cross sections crossed the dune at the breach.

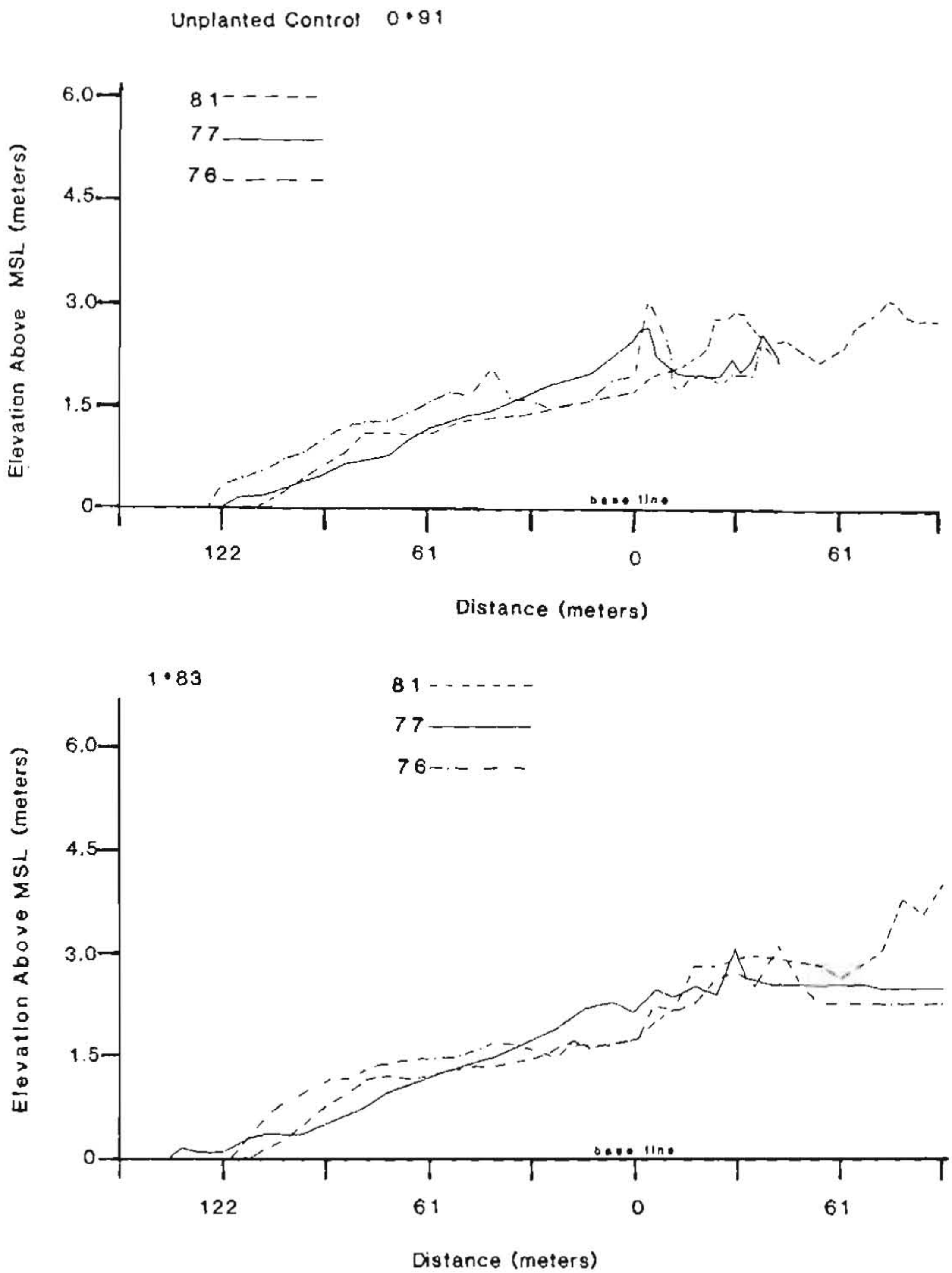
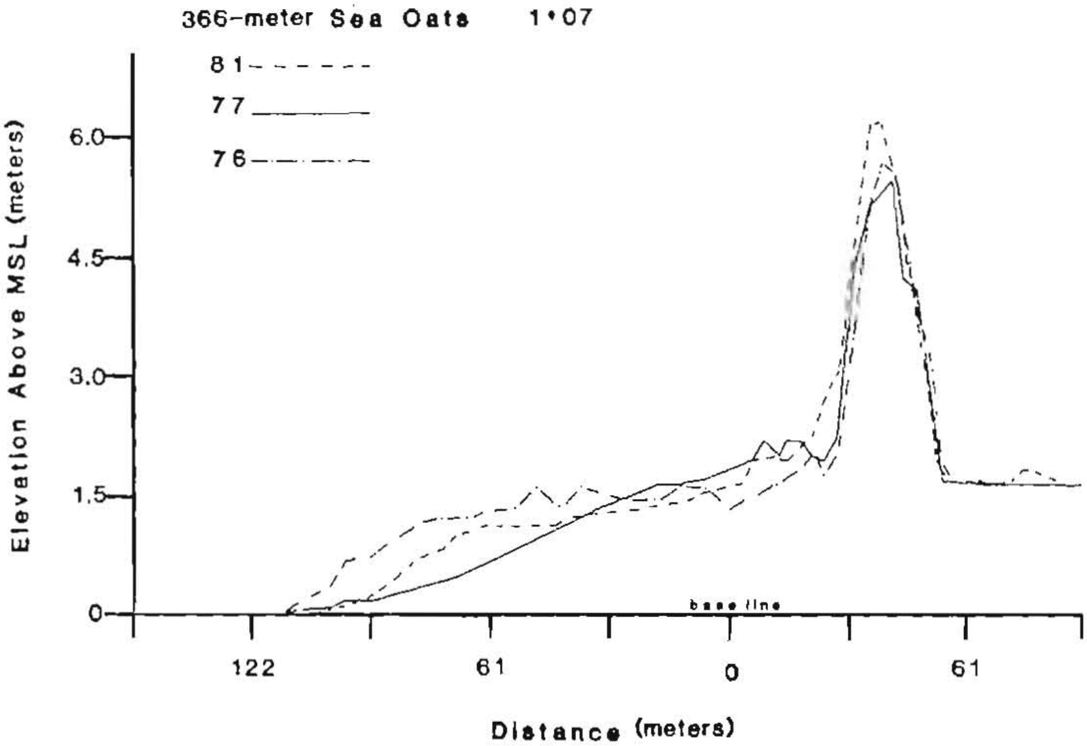


Figure 8. Cross-sectional beach and foredune profiles for the unplanted natural area.



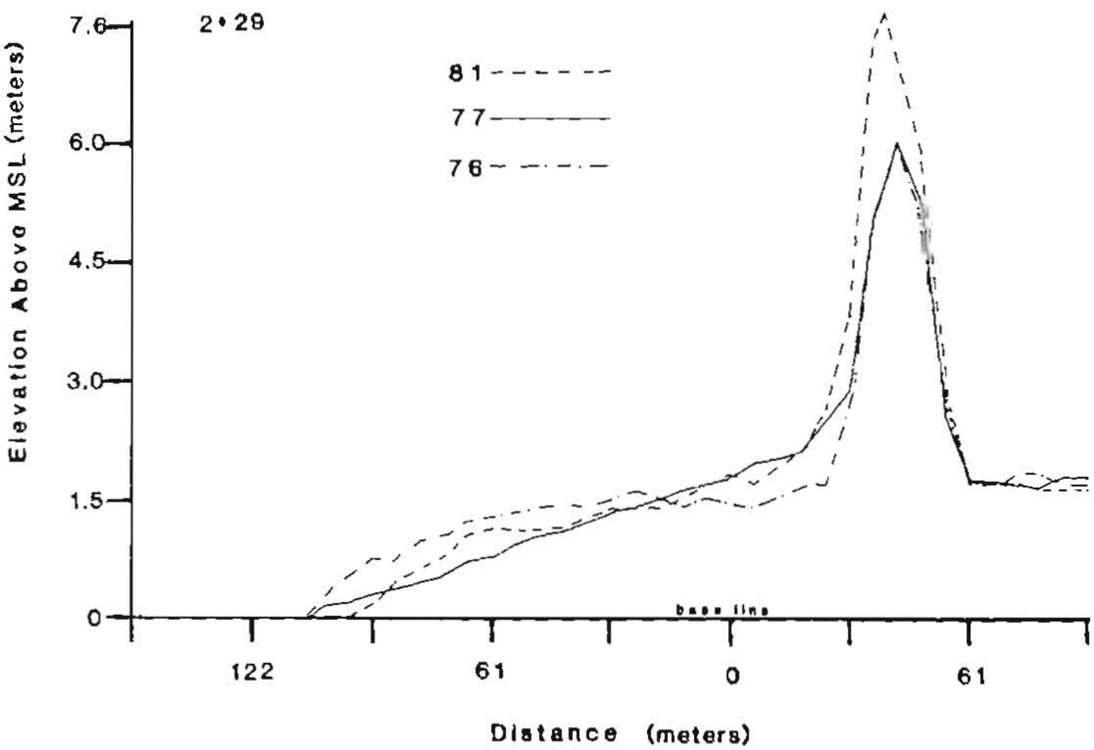


Figure 9. Cross-sectional beach and foredune profiles for the 366-meter sea oats dune.

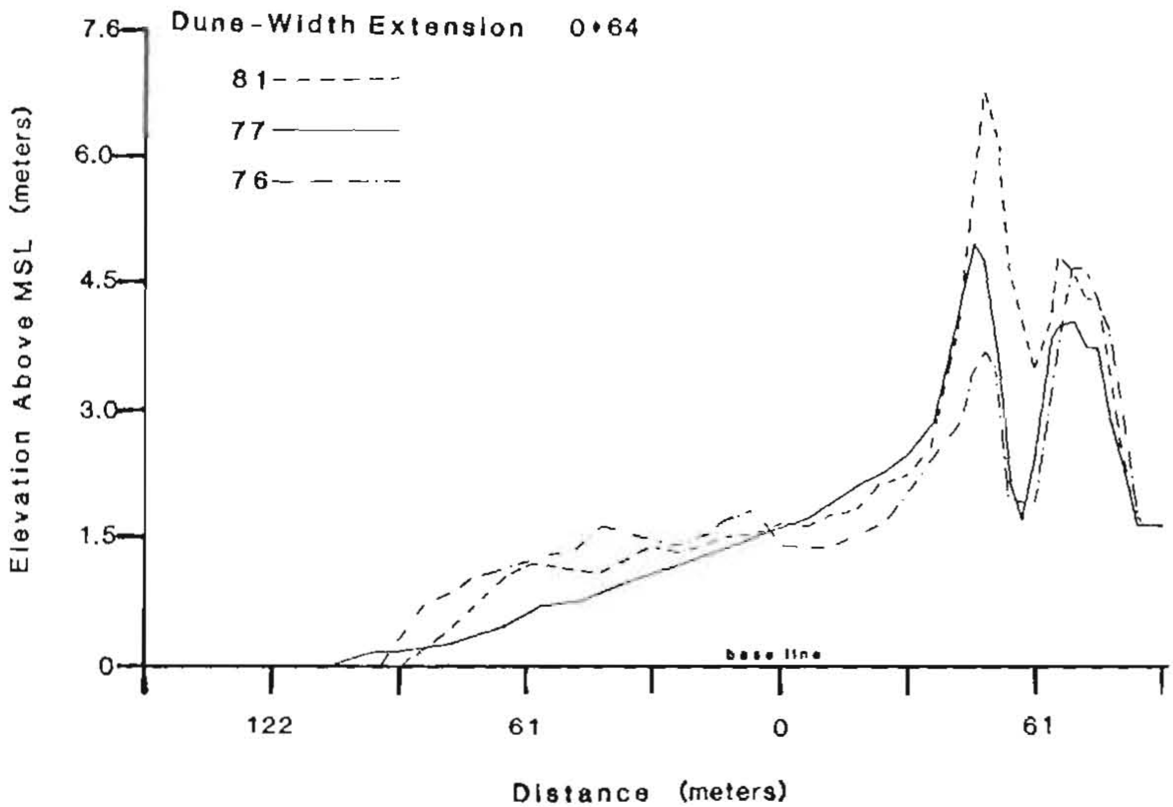


Figure 10. Cross-sectional beach and foredune profiles for the dune-width extension dune.

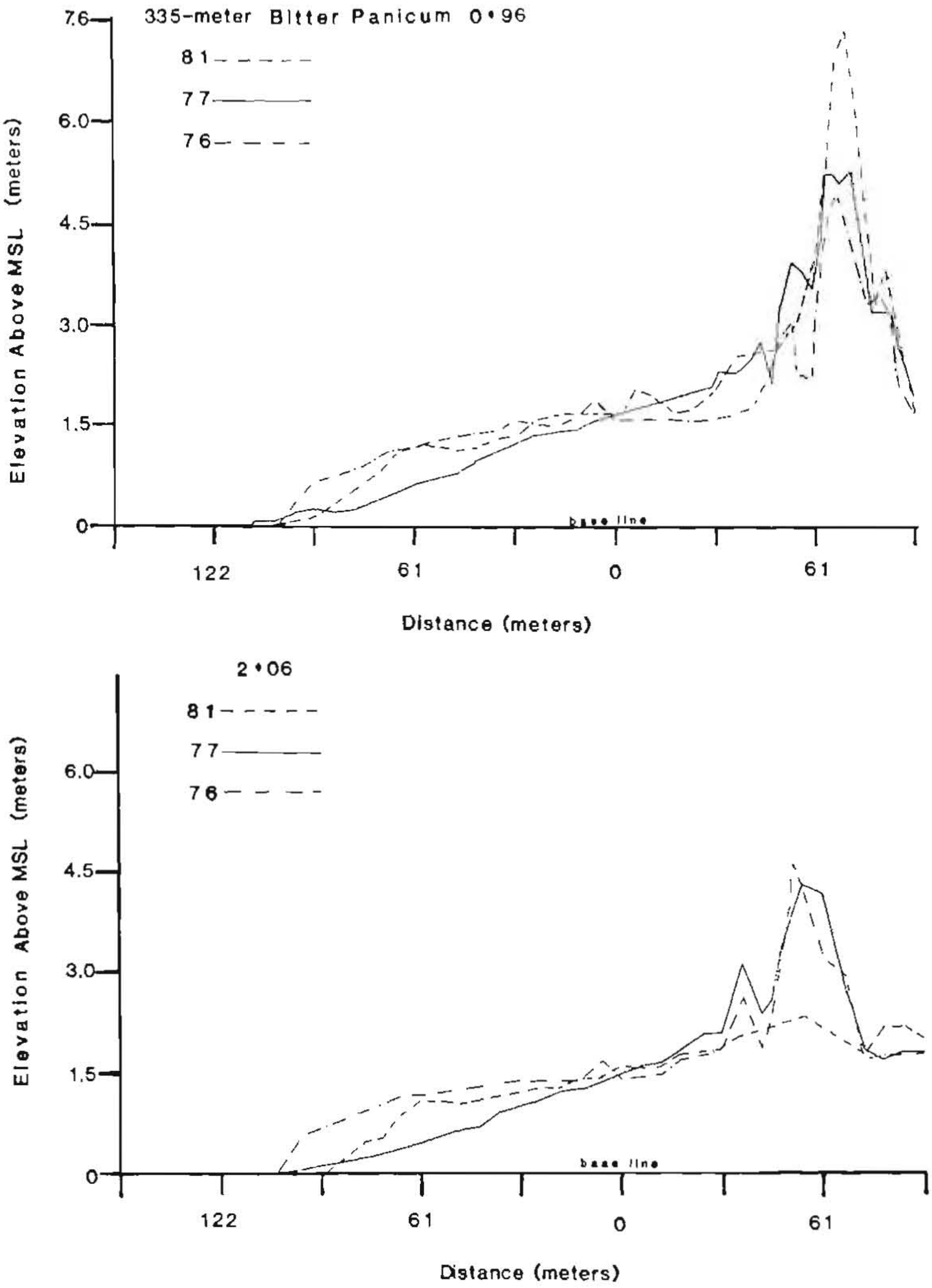


Figure 11. Cross-sectional beach and foredune profiles for the 335-meter bitter panicum dune.

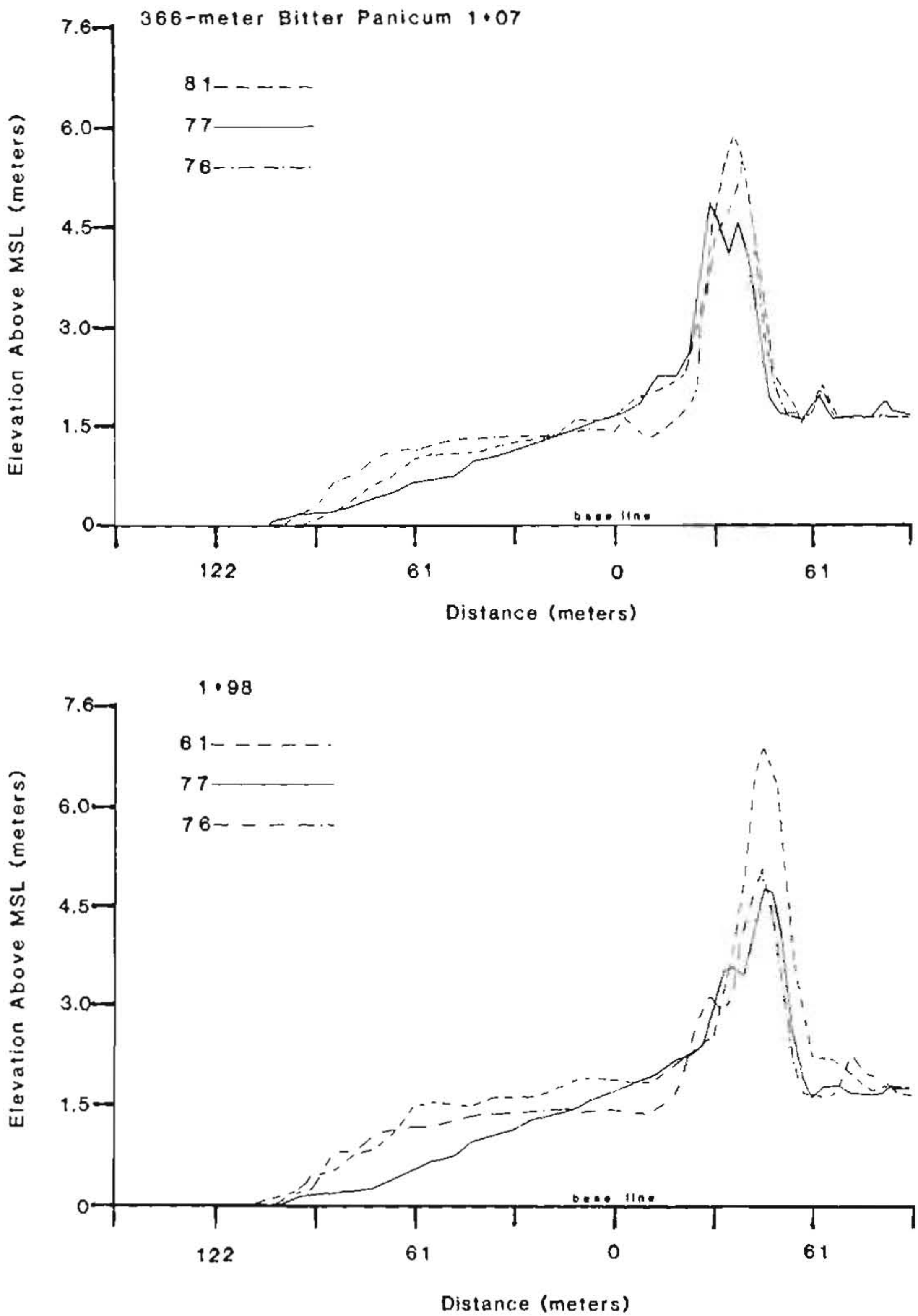


Figure 12. Cross-sectional beach and foredune profiles for the 366-meter bitter panicum dune.

sand volume data from Hurricane Anita should be used since measurements were taken within a month of that hurricane. Except for the 366-meter bitter panicum dune, the foredune segments all accumulated sand from August 1976 to September 1977, despite Hurricane Anita. Thus, the erosion of sand following Hurricane Anita was entirely from the beach--and not really a loss at all--just a temporary displacement into the gulf.

The net accumulation of sand in this 200-meter segment indicates that some new sand, probably from longshore currents, was deposited on the beach, and it was then windblown into the foredune and trapped in the vegetation. From March 1975 to March 1981 the average net sand accumulation per linear meter of beach for all profiles was 69.5 cubic meters. This was 61.0, 58.8, 105.8, 47.3, and 78.5 cubic meters for the unplanted, 366-meter sea oats, dune-width extension, 335-meter bitter panicum, and 366-meter bitter panicum area, respectively (Table 2). This is an annual accumulation of new sand of 11.5 cubic meters per meter of beach. Note that the dune-width extension with its wider base accumulated considerably more sand than the other plantings.

b. Sand Volumes Above Planting Elevation for 30-meter Segment of the Foredunes. The only sand volumes measured from early in the initial study were from those areas immediately affected by the 15-meter-wide test plantings (Dahl, et al., 1975). About 8 meters on either side of the plantings were measured beginning in 1970. The 1970 measurement is reported in Table 3, along with the 1977 and 1981 surveys for comparison purposes. The dune-width extension plantings were not included. It is apparent that the beach plantings adequately trapped the migrating beach sand as intended. However, Hurricane Allen did remove several cubic meters from the unplanted control study area. Much of this sand was transported farther inland (Table 2).

c. 88-meter Segment of the Foredune. Because the plantings influenced sand accumulation for more than 30 meters in 1975, sand volumes were measured for an 88-meter dune segment extending from 30 meters seaward of the grass planting to 58 meters landward.

The total sand accumulation in this 88-meter segment of the unplanted control areas was well below that for the dunes resulting from the beach-grass plantings (Table 4). The data in Table 2 show that this eroded sand was transported farther inland. The major difference between this area and the planted dune areas is that the planted dunes present a solid wall of resistance to the sand being transported inland. Therefore, migrating sand from the beach accumulates on the dune face. On the unplanted area, the front "wall" is not solid, so migrating sand penetrates through and over a broader base. The result is a relatively high "floor," around 2.6 to 3.0 meters MSL, among the scattered hummock dunes. In contrast, the floor elevation behind and among the dunes of the planted study areas is only from 1.7 to 2.1 meters MSL. The planted areas have accumulated sand at higher elevations.

2. Dune Base Width.

According to the Dahl and Goen (1977) report, the planted grasses on the experimental dunes spread laterally between 1.5 to 2.1 meters per year, based on the 1975-1976 measurements. Because Padre Island has now had a major hurricane, and it is difficult to assess the rate of grass spread, an evaluation is made of the rate of dune widening from the cross-sectional

Table 3. Sand volumes accumulated above planting elevation for the immediate locale of planting.[1]

Location	Planting elevation (m)	Volume by survey date (m^3/m)													
		1970		1971		1972		1973	1974	1975		1976		1977	1981
		May	Aug.	May	Aug.	Apr.	July	May	Mar.	Mar.	Aug.	Mar.	Aug.	Sept.	Mar.
Unplanted area	1.2								12.0	19.0	21.9	22.8	26.2	39.4	18.5
366-meter sea oats	1.2	5.3	6.8	22.8	27.8	41.9	40.1	50.2	53.4	71.2	79.5	82.5	84.8	93.4	106.6
335-meter bitter panicum	1.3				17.3	18.6	25.1	29.3	45.7	53.9	57.7	62.0	64.7	73.9	94.7
366-meter bitter panicum	1.6							7.5	21.3	38.6	44.1	45.4	54.4	61.8	86.3

[1] Planting width, 15 meters; surveyed distance, 30 meters.

Table 4. Sand volume for beach cross sections from 30 meters in front of dunes to 58 meters across the dunes.

Location	Mar. 1975	Aug. 1975	Mar. 1976	Aug. 1976	Sept. 1977	Mar. 1981
	Volume by survey date (m^3/m)					
	Total volume					
Unplanted area	168.8	172.1	173.6	182.4	219.7	173.3
366-meter sea oats	207.9	217.7	220.2	223.5	244.0	256.4
Dune-width extension	207.7	215.2	218.2	225.8	253.2	279.8
335-meter bitter panicum	210.0	217.2	221.0	225.8	242.3	262.2
366-meter bitter panicum	184.6	190.1	192.1	204.2	219.5	250.0
	Volume above planting elevation[1]					
Unplanted area	61.2	64.5	66.0	74.5	112.5	65.5
366-meter sea oats	100.3	109.9	112.6	115.6	136.2	148.6
Dune-width extension	89.3	96.6	99.6	109.4	134.7	161.2
335-meter bitter panicum	91.3	98.8	102.6	107.1	123.8	143.7
366-meter bitter panicum	44.4	50.2	51.9	64.2	79.4	109.9

[1]Planting elevations: unplanted area, 1.2 meters; 366-meter sea oats, 1.2 meters; dune-width extension, 1.3 meters; 335-meter bitter panicum, 1.3 meters; 366-meter bitter panicum, 1.6 meters.

elevations. The planted dunes rise abruptly at about 2.4 meters above MSL; therefore, the width of the dune was recorded between the area where elevations rise above 2.4 meters MSL on the seaward side and where they drop below 2.4 meters MSL on the bay side of the dunes (Table 5). This showed that the dunes continue to widen at about 1.8 to 2.4 meters per year. The naturally formed dune, north of the Ranger Station access road, also apparently grew in width at about the same rate.

The unplanted control section grew in a different way. Because no uniform line of plants existed naturally, the sand was not trapped in a narrow strip, but accumulated over a broad base of about 91 meters. Consequently, accumulating sand was spread over almost the entire 91-meter width. In March 1976 few of the elevations exceeded 2.4 meters MSL. By 1977 the dune width over 2.4 meters above MSL increased to about 30 meters. By 1981, the full 91 meters had elevations 2.4 meters above MSL or higher (Table 5), except for about 9 meters in the middle of two of the transects. When this section becomes a mature dune it will have a broad base which is similar to other naturally formed dunes.

The planted experimental dunes have a base width from 37 to 53 meters (Table 5). Naturally formed dunes in the area have a base width over 80 meters and probably most are more than 91 meters. Though the planted dunes have narrower bases, there are advantages to providing a uniform sand-trapping field immediately following dune erosion as occurs during severe storms such as Hurricane Carla in 1961 or Hurricane Allen in 1980:

(1) A dam is rapidly built to help stop future storm waters from crossing the island to flood the mainland areas.

(2) Highly mobile sand is rapidly confined to one area of accretion, hence it is not lost to the beach system.

(3) The resultant wall of accumulating sand prevents inland movement of saltwater from annual storm surges of moderate intensity. At the same time, the accumulating sand acts as a dam for rainwater providing a mesic environment that is free from saltwater on the seaward side of the plantings so that salt-intolerant vegetation can become rapidly established.

(4) After moderate accumulation of sand, little salt spray penetrates beyond the forepart of the planted dune, further hastening the establishment of the island vegetation intolerant of salt spray.

During the experimental plantings from 1960 to 1974, the 366-meter bitter panicum and the dune-width extension plantings were specifically made to find the most effective way to widen the base of dunes constructed from vegetation plantings. Techniques for increasing the base width of the planted dunes are described in Dahl and Goen (1977).

Table 5. Base width of measured dunes in 1981. Measurements show dune width between increasing elevations above 2.4 meters MSL on the seaward side and decreasing elevations below 2.4 meters MSL on the landward side.

STUDY DUNES	Width of dune base (m)					
	North half			South half		
	1976	1977	1981	1976	1977	1981
Unplanted control dune	15.2	39.6	91.4[2]	9.1	24.4	91.4[2]
366-meter sea oats	29.0	30.5	33.5	30.5	36.6	39.6
Dune-width extension	38.1	45.7	50.3	42.7	51.8	53.3
335-meter bitter panicum	30.5	53.3	56.4	30.5	33.5	39.6[1]
366-meter bitter panicum	21.3	24.4	29.0	27.4	30.5	36.6

NATURAL DUNES	1974	1981
91 meters North of Ranger Station Access Road	70.1[2]	82.3[2]
Pedestrian Traffic (18 meters south)		91.4
Pedestrian Traffic (2.25 kilometers south)		79.2
Pedestrian Traffic (2.6 kilometers south)		91.4

[1]Does not include the one cross section where the hurricane breach occurred.

[2]Dune width values for natural dunes show that at least the indicated width of dune is 2.4 meters above MSL.

3. Dune Crest Elevation.

Longitudinal surveys that paralleled the beach were made along the crests of all the planted dunes. No definable dune existed in the unplanted study area prior to 1981; therefore, no longitudinal survey was made until that year. Figure 13 graphically shows the crest survey data. The longitudinal figures are more revealing than the cross-sectional figures for ascertaining the effective height of dunes. It is also easier to show where relatively more sand is accumulating. The profiles also provide an instant evaluation of the effectiveness of the overall dune-building research. Although some low areas through the dunes begin to heal in time, some are quite persistent and may require mechanical repair to completely heal; e.g., most deep cuts present in March 1975 were still evident in August 1976 and some were even still present in 1981. The repair of these low areas should be further researched. Stacking bales of hay in the cuts and tying the bales to the canyon walls with netting to reduce the wind velocity may help these areas fill with sand. Some low areas have filled in naturally through time. The one major breach occurring in the experimental dunes from Hurricane Allen (Fig. 13) occurred in a relatively high area in the dune ridge. This would suggest that changes in the beach and offshore zone during a storm may be more important than the dune crest elevation in determining the location of overwash events.

4. Shoreline Changes.

Hurricane activity has resulted in minimal long-term changes on the shoreline protected by the study dunes as evidenced by total sand volumes. However, immediately following a major hurricane, such as Hurricane Anita in 1977, 31.5 cubic meters per meter of beach was eroded from the beach segment of the study dunes (Table 2). A part of the eroded beach sand was deposited higher on the foredune segment, but most of it was transported seaward into the gulf (Figs. 8 to 12). The wave and tide action apparently redeposited this sand on the beach within a few months. Undoubtedly, Hurricane Allen transported even more sand from the beach into the gulf than Hurricane Anita, but the 7-month period between the hurricane and the survey allowed redeposition of most of the eroded beach sand (Table 6).

5. Naturally Formed Dunes versus Experimental Dunes.

In studies made over the past 10 years, the existing dunes that survived the hurricanes in the 1960's were not monitored. However, a survey was made on one cross section of a naturally formed dune in 1974 and remeasured in 1981 (Fig. 14). This cross section is about 91 meters north of the entrance to the beach from the Ranger Station access road. Also, the Padre Island National Seashore had a number of cross sections surveyed on north Padre Island on 3 August 1980, only a few days before Hurricane Allen. Although these latter measurements do not include the landward side of the dunes, they do provide a way to further estimate the meters accreted in naturally formed dunes. Remeasurement was made of three of the transects that ran perpendicular to the pedestrian segment of the beach, but having no vehicular use (Fig. 14; Table 7).

The 108-meter beach segment differed little in sand volume on experimental dune areas with 123 cubic meters per meter and natural dune areas

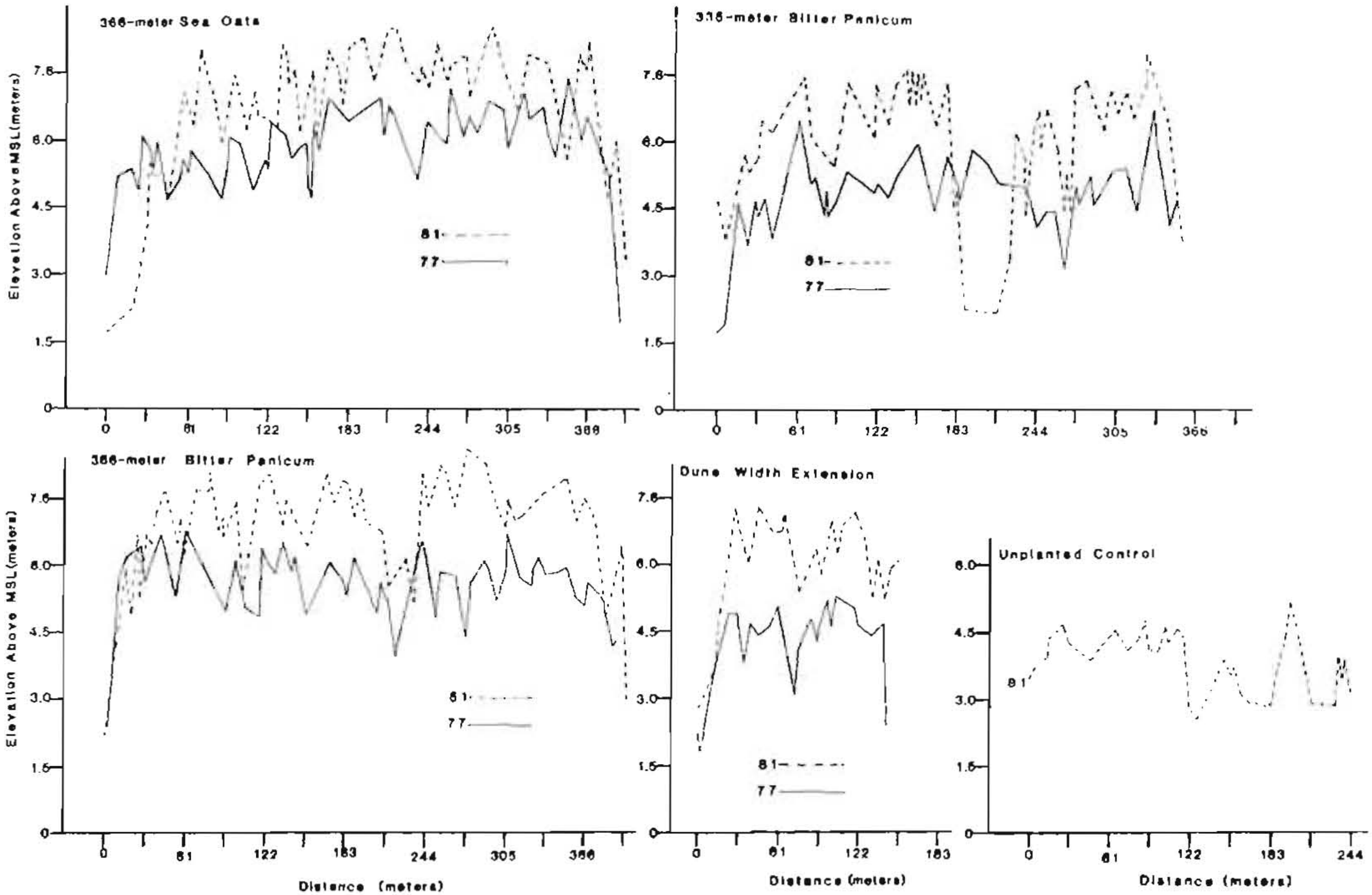


Figure 13. Longitudinal profiles along dune crests for experimental dunes and the unplanted control area.

Table 6. Distances from the east base line to MSL for the study locations with beach cross-sectional profiles.

Beach profile	Distance by survey date (m)					
	Mar. 1975	Aug. 1975	Mar. 1976	Aug. 1976	Sept. 1977	Mar. 1981
Unplanted natural area						
1 + 83 station	110	122	126	120	138	114
0 + 91 station	127	132	119	124	121	112
366-meter sea oats						
1 + 07 station	111	122	110	112	113	109
2 + 29 station	103	119	107	105	108	98
Dune-width extension						
0 + 64 station		93	102	92	110	91
335-meter bitter panicum						
0 + 96 station	101	97	89	103	111	102
2 + 06 station	100	100	119	108	104	92
366-meter bitter panicum						
1 + 07 station	88	105	106	101	105	95
1 + 98 station	104	100	106	101	102	109
Avg. (all stations)	105	111	109	108	113	102

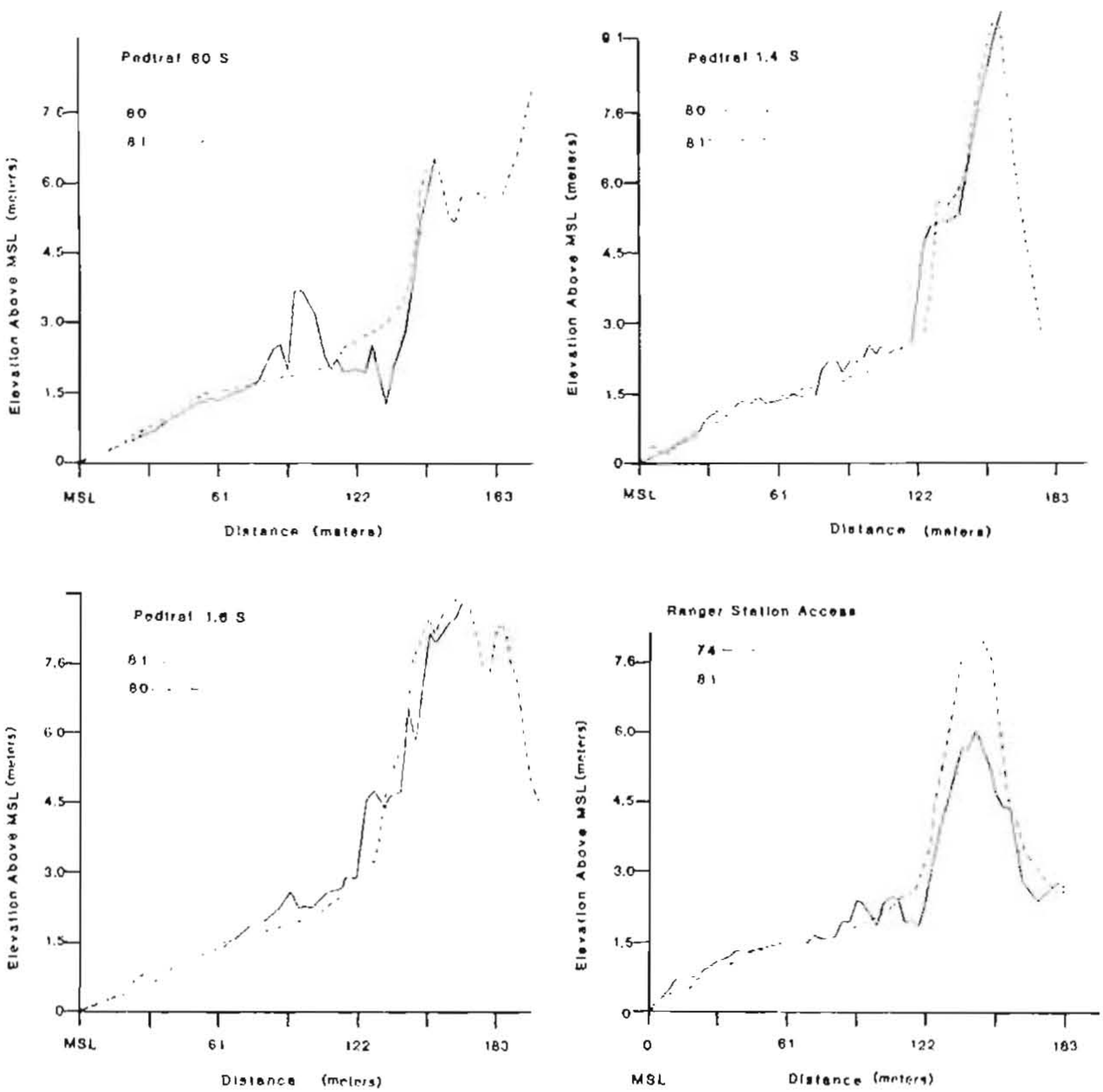


Figure 14. Cross-sectional beach and foredune profiles for existing natural dunes.

Table 7. Sand volume for beach and foredune cross sections of existing naturally formed dunes.

NATURAL DUNES	Volume by survey date (m^3/m) 1974	1980	1981
Beach segment (MSL to 108 meters)			
91 meters North of Ranger Station Access Road	152.5		137.7
Pedestrian Traffic - 18.3 meters South		154.5	132.9
Pedestrian Traffic - 2.3 kilometers South		143.0	131.4
Pedestrian Traffic - 2.6 kilometers South		142.0	136.5
Foredune segment (108 meters to 200 meters)			
91 meters North of Ranger Station Access Road	326.1		401.3
Pedestrian Traffic - 18.3 meters South		408.9	436.7
Pedestrian Traffic - 2.3 kilometers South		435.7	432.2
Pedestrian Traffic - 2.6 kilometers South		570.4	569.2
Total segment (MSL to 200 meters)			
91 meters North of Ranger Station Access Road	478.6		539.1
Pedestrian Traffic - 18.3 meters South		562.1	569.7
Pedestrian Traffic - 2.3 kilometers South		578.7	563.6
Pedestrian Traffic - 2.6 kilometers South		712.4	705.6

with 135 cubic meters per meter. However, the natural foredune had a volume of 459 cubic meters compared with only 258 cubic meters in the experimental dunes (Table 4). The annual rate of new sand accumulations to the beach and foredunes was about 9.3 cubic meters per meter of beach since 1974 on the dune near the Ranger Station access road, which is less than the 11.5 cubic meters per year being added to the experimental dune areas since 1975. Dune crests of natural dunes are no higher, about 7.6 to 8.2 meters MSL, than the experimental dunes resulting from grasses planted in 1969 to 1972. However, the natural dunes are much wider at the base. Plants becoming established naturally do not grow in parallel rows nor are they spaced as closely together as when planted by man. Consequently, sand is blown inland from the beach in and around pioneer plants, but much of it passes on through, accumulating over a broad area and extending 244 to 274 meters landward from MSL. The unplanted control area in the experimental dunes now has a sand floor for tbe newly forming dune 2.6 to 3.0 meters above MSL. The way dunes form naturally can be approximated from the data accumulated on the unplanted control section. Hurricane Allen caused erosion of the sand in front of this section, leaving the pioneer vegetation in line with the other naturally formed dunes. A new dune line is now distinguishable (Fig. 3) and crests are already 4.0 to 4.6 meters above MSL. This area is expected to take on a definite dune form within the next 2 to 5 years and it should have a relatively broad base. It appears that about 25 years (from Hurricane Carla in 1961) is required for an effective dune to reform naturally on north Padre Island. This would be true, however, only if no major storm occurred during the interim with sufficient energy to erode the newly forming foredunes. It is desirable to plan for a broad based dune at the outset for any dunes to be constructed from planted vegetation.

6. Coastal Vegetation.

a. Vegetation on Experimental Foredunes. In the experimental foredune plantings, Dahl and Goen (1977) reported sea oats and bitter panicum have spread seaward about 1.6 meters per year. Apparently, both species continue to spread at about the same rate.

Invasion of unplanted species into the experimental foredunes continues to be extremely slow. Gulf croton increased significantly only on the 366-meter sea oats dune (Table 8) and, except for occasional plants of beach groundcherry and beach morning glory, no other species have occurred even after 12 years.

Although many other species can tolerate salt spray, some protection from salt spray allows for better survival. The older planting (landward dune of the dune-width extension dune made in 1969 and 1970, Table 1), has invading plants of several other species (Table 8). The shelter provided by accumulating sand, resulting from the 1973 seaward planting of bitter panicum, has allowed establishment in the landward crest of the dune-width extension dune of prairie senna, beach evening primrose, beach morning glory, beach groundcherry, Corpus Christi fleabane (*Erigeron myrionactis*), and gulf croton. Trace amounts of several other species also occur.

On the unplanted control area, where a natural dune is reforming, pioneer plants are primarily beach morning glory and sea oats, with *Fimbristylis* spp., gulf croton, and beach evening primrose being common. An occasional bitter

Table 8. Importance values[1] (IV) for common species (planted and invading) for experimental foredunes for 1975, 1976, and 1981. Values are the mean of seaward and landward transects except the last two columns show differences between species establishing on exposed and protected dunes.

	Unplanted natural area			366-meter Sea oats			Dune-width extension			335-meter Bitter panicum			366-meter Bitter panicum			Dune-width extension (1981) Front Dune (seaward)	Back Dune (Landward)
	75	76	81	75	76	81	75	76	81	75	76	81	75	76	81	81	81
Eragrostis oxylepis	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2
Eragrostis spectabilis	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Panicum amarum	0	0	3	50	214	124	1410	3532	2648	1344	2437	1433	2716	4912	2410	2648	792
Spartina patens	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Sporobolus virginicus	1	8	1	0	0	0	0	0	2	0	0	0	0	0	0	2	0
Uniola paniculata	51	89	246	691	2035	854	0	2	0	36	80	7	4	14	32	0	816
Fimbristylis spp.	6	0	71	0	0	1	0	0	0	0	0	0	0	0	0	0	0
Cassia fasciculata	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Croton punctatus	89	314	12	1	5	265	0	0	2	0	4	11	0	1	14	2	36
Euphorbia ammannioides	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5
Oenothera drummondii	12	74	4	2	44	2	1	2	10	8	55	0	1	0	1	10	371
Ipomoea pes-caprae	9	4	2	1	5	0	0	1	0	7	7	1	1	0	0	0	0
Ipomoea stolonifera	799	1255	459	1	0	0	0	0	4	2	19	74	0	0	0	4	1005
Physalis viscosa	0	1	1	0	2	37	0	0	3	0	1	12	0	0	2	3	190
Erigeron myriocactis	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	180

[1] IV - product of percent frequency X percent coverage.

panicum plant occurs. Lack of a seed source probably relegates it to a secondary role in this area. Most of the bitter panicum commonly occurring in the experimental dune vicinity probably originated from imported planting materials, which came from south Padre and Mustang Islands.

b. Vegetation Behind (Landward) Experimental Foredunes. The most obvious difference between the unplanted, natural area landward of the normal dune line and that of the same area behind the experimental plantings is the vegetation density and cover. Because no well-defined dune existed on the unplanted area, Hurricane Allen redistributed much of the sand in the random patches of preexisting vegetation and sand from the backshore, spreading it landward over the area of the normal dune line. Thus, much of the existing vegetation was covered. The ground cover decreased from 28 percent in 1976 to 17 percent in 1981 (Table 9).

Because well-developed dunes exist from experimental plantings, Hurricane Allen transported sand inland only between dunes and at the breach in the 335-meter bitter panicum dune. Consequently, a well-developed grassland now exists landward of the experimental dunes with 56 percent ground cover, up from only 39 percent in 1976 (Table 9). The hurricane-deposited sand occurred only locally; therefore, it covered little vegetation. The area landward of the experimental dunes is relatively low in elevation and fresh rainwater tends to pond there, producing vegetation with a marshy-type component in the local low spots. Species, such as gulfdune paspalum, American bulrush (*Scirpus americanus*), *Fimbristylis* spp., largeleaf pennywort (*Hydrocotyle bonariensis*), coast brookweed (*Samolus ebracteatus*), sand rosegentian (*Sabatia arenicola*), and longleaf flaveria (*Flaveria oppositifolia*) occurred commonly in these lower areas (Table 10).

Sea oats, bitter panicum, and shoredune panicum (*Panicum amarulum*) invaded rapidly on this landward area following the experimental dune plantings in the early 1970's. Sea oats populations appear to have stabilized, but the *Panicum* species have increased substantially since 1976 (Table 10). Most of the *Panicum* appears to be bitter panicum, but the breakup of clumps of the bunch-type bitter panicum made exact identification difficult. Most of the plants encountered were judged to be bitter panicum. Bermuda grass (*Cynodon dactylon*) and seashore dropseed were common in local areas in 1976 and had changed little overall by 1981. Saltmeadow cordgrass was common behind the 336-meter sea oats dune, but was mostly absent elsewhere. Red love grass (*Eragrostis oxylepis*) occurred occasionally in 1975-76, but was quite common in 1981. Also, purple love grass (*Eragrostis spectablis*) was occasionally encountered. Behind all the experimental dunes prairie senna and Corpus Christi fleabane were abundant and had increased during 1976 (Table 10). The latter species occupied the less marshy or drier sites on the lowlands behind the experimental foredunes.

c. Vegetation in Front (Seaward) of the Experimental Foredunes. Hurricane Allen denuded essentially all the beach (including the backshore) back to the foredunes (Fig. 15). However, live shoots were common everywhere from perennial grass roots and rhizomes, particularly of sea oats and bitter panicum, adjacent to the experimental dunes. In addition, new shoots of saltmeadow cordgrass were common on the formerly vegetated beach of the "pedestrian only" area north of Malaquite Beach (Fig. 7). These new shoots

Table 9. The percent of coverage for all vegetation from transects measured at various locations in the five study areas for 1975, 1976, and 1981.

Transect Location

	On Foredune						Landward of Foredunes									On Foredune			Landward of Foredunes		
	Seaward			Landward			8 meters West			38 meters West			69 meters West			(average)			(average)		
	75	76	81	75	76	81	75	76	81	75	76	81	75	76	81	75	76	81	75	76	81
Unplanted Natural Area	9	27	15	22	30	20	27	25	10	20	31	17	21	27	25	16	28	18	23	28	17
366-meter Sea Oats	12	31	34	12	39	21	27	40	58	31	35	63	42	40	58	12	35	28	33	38	60
Dune-Width Extension	21	52	37	17	40	31	15	18	54	28	71	54	30	57	45	19	46	34	24	49	51
335-meter Bitter Panicum	23	36	31	19	45	24	17	42	61	23	33	63	31	42	63	21	40	28	23	39	62
366-meter Bitter Panicum	28	61	51	28	41	29	17	24	57	12	18	53	25	44	43	28	51	40	18	29	51
Average of Planted Dunes	21	45	38	19	41	26	19	31	58	23	39	58	32	46	42	20	43	32	24	39	56

Table 10. Importance values[1] (IV) for common species becoming established within 69 meters of the planted dunes (landward) for 1975, 1976, and 1981.

	Unplanted natural area			366-meter Sea oats			Dune-width extension			335-meter Bitter panicum			366-meter Bitter panicum		
	75	76	81	75	76	81	75	76	81	75	76	81	75	76	81
Cynodon dactylon	1	1	0	46	7	0	7	2	1	0	1	23	0	0	2
Eragrostis oxylepis	0	0	0	0	0	23	0	0	17	0	0	120	0	0	68
Panicum amarum	0	0	9	93	123	473	52	7	116	61	134	231	101	84	194
Paspalum monostachyum	0	2	2	20	125	240	0	0	5	T[2]	T	170	0	0	9
Spartina patens	0	0	6	0	3	188	0	0	0	1	0	0	1	1	3
Sporobolus virginicus	T	1	2	229	248	76	45	15	370	8	6	23	1	3	6
Uniola paniculata	1	T	0	21	57	14	43	93	118	110	281	105	138	204	241
Fimbristylis spp.	28	2	126	495	121	145	420	505	133	90	500	174	168	138	174
Scirpus americanus			13			230			199			41			14
Cassia fasciculata	1	109	17	10	37	21	6	55	228	239	170	768	24	87	557
Croton punctatus	283	166	7	3	1	1	2	2	0	6	1	6	10	7	2
Oenothera drummondii	217	155	31	91	131	4	260	210	49	203	332	230	186	236	166
Hydrocotyle bonariensis	1	2	13	341	148	327	9	13	49	3	15	78	0	1	24
Samolus ebracteatus	1	1	0	37	61	232	5	143	317	1	25	166	1	29	177
Sabatia arenicola	0	33	0	25	25	73	37	31	212	10	20	50	20	30	95
Ipomoea stolonifera	609	719	306	3	3	3	175	389	51	57	42	68	7	49	7
Bacopa monnieri	1	24	0	167	11	0	26	1	1	4	1	0	2	11	1
Erigeron myrionactis	1	27	0	6	5	79	18	7	320	3	76	234	2	25	324
Flaveria oppositifolia			0			125			430			86			12

[1] IV = product of percent frequency X percent coverage.

[2] T = less than 0.5 percent.

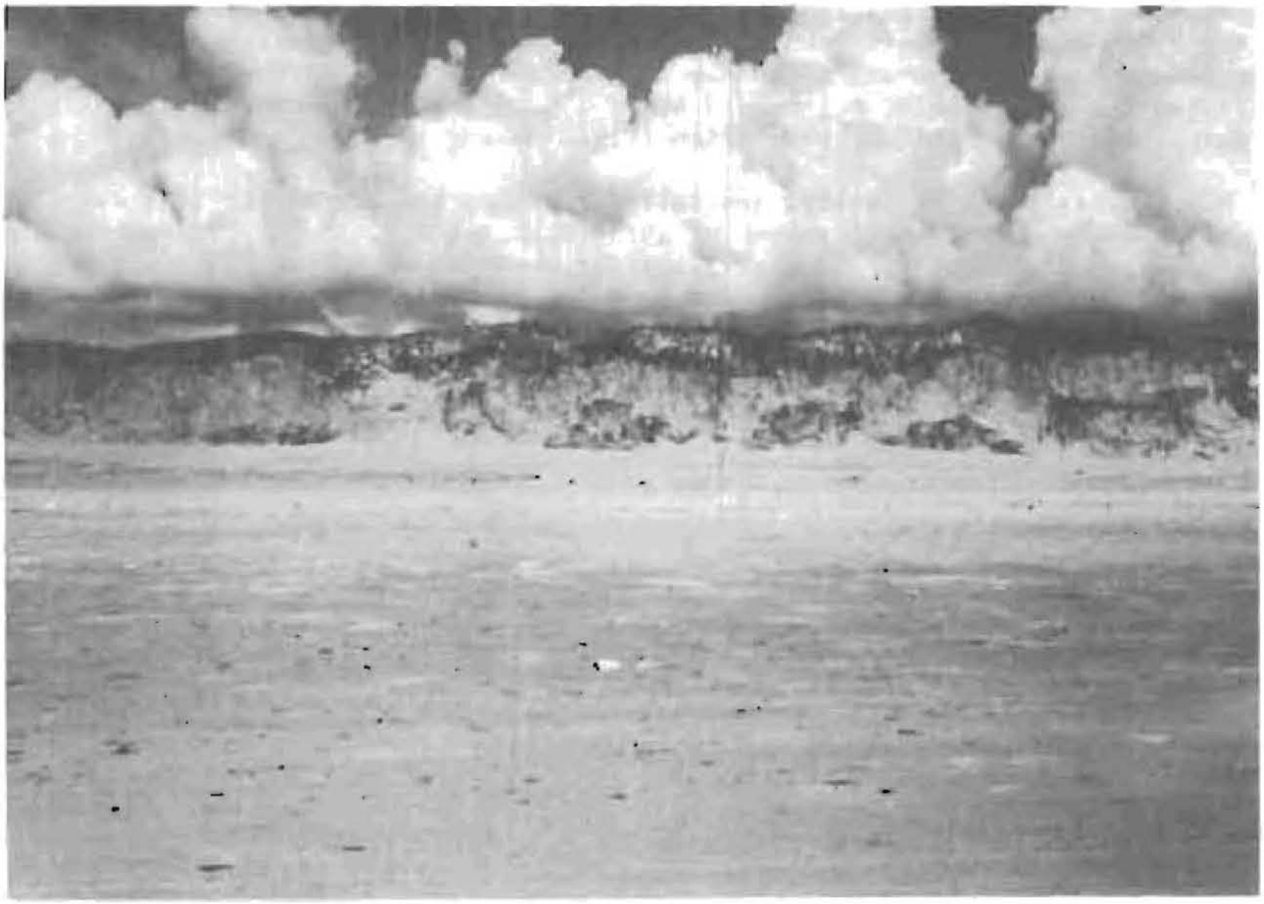


Figure 15. The bitter panicum dune (366 meters) in August 1980 showing a vertical cliff caused by Hurricane Allen.

appeared to be accumulating sand and a rapid recovery of both sand and vegetation on this section of Padre Island is anticipated.

In 1961 Hurricane Carla removed the sand to about 1.2 meters MSL on many north Padre Island areas and essentially eliminated all the plant roots and rhizomes. The 1969 plantings were made at 1.34 meters above MSL, 8 years after the hurricane. With current beach elevations near the normal 1.5 to 1.8 meters above MSL, and with much residual plant material, immediate and substantial sand trapping is expected in front of the existing natural and experimental dunes.

d. Midisland Dune Field. Bare dune fields activated, in part, early this century by overgrazing and drought migrate westward (landward) across Padre Island. The active dunes are so unstable that colonization by plants does not occur. However, after the dune migrates past a given point, it leaves behind a zone of moist sand about 1.5 to 1.8 meters above MSL, which is then rapidly colonized by vegetation (Figs. 16 and 17).

An area 91 by 46 meters, generally on the north side of the live oak motte, was sampled in the summer of 1973 (Dahl, et al., 1975). It was found that the most important colonizing species were common bermuda grass, red love grass, and species of *Cyperus* and *Juncus*. A resampling of this area was made in July 1981. To show plant successional trends from bare sand to a more mature grassland, samples of the area were made in 76-meter blocks, including an area of mostly bare sand immediately adjacent to the migrating sand dunes (Table 11). The current data, like that of the 1973 sampling, showed that five vegetative species were early colonizers: bermuda grass, red love grass, *Fimbristylis* spp., *Cyperus* spp., and needlepod rush (*Juncus scirpoides*). Vegetation covered only 2 to 3 percent of the sand surface of the 76 meters most recently abandoned by the migrating dune field.

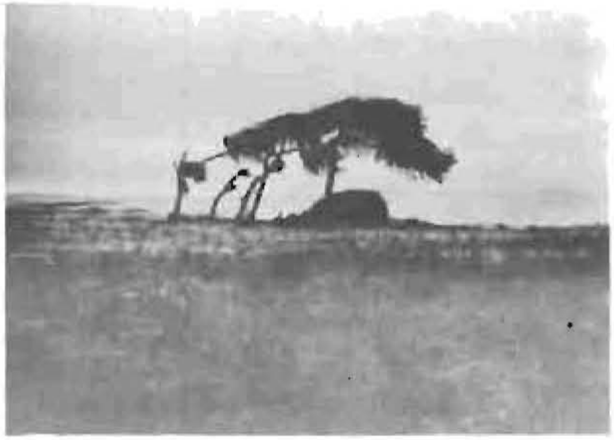
The 76 meters farther east had 25 percent vegetation cover and about 11 more plant species. Additions to the list of early colonizers were seacoast bluestem, spike rush species (*Eleocharis* spp.), prairie senna, Corpus Christi fleabane, beach evening primrose, plains coreopsis (*Coreopsis tinctoria*), Texas ironweed (*Vernonia Texana*), Juniperleaf polypremum (*Polypremum procumbens*), and green carpet weed (*Mollugo verticillata*).

From 152 to 229 meters away from the bare dunes, vegetation cover increased to 42 percent, and 25 species were encountered. Between 229 and 305 meters away from the migrating dunes, the vegetation ground cover increased to 56 percent with 21 species encountered; nine of them dominated the composition. They were: seacoast bluestem, gulfdune paspalum, *Paspalum* spp., (*Panicum oligosanthes*), red love grass, needlepod rush, prairie senna, camphor weed (*Heterotheca pilosa*), and Corpus Christi fleabane. As the vegetation community became more mature bermuda grass disappeared from the composition (Table 11).

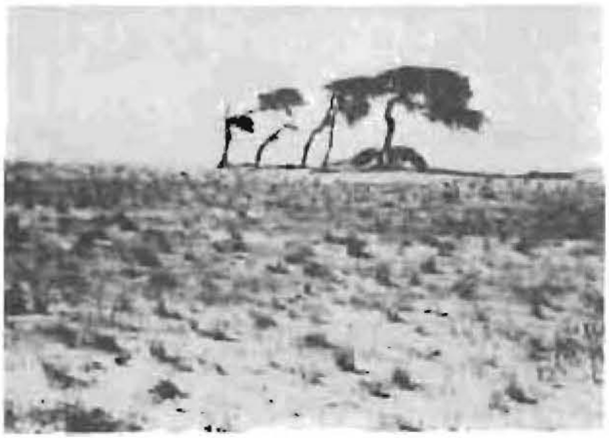
Depressions holding water for longer periods after rainfall had primarily: American bulrush, spikerush, waterhyssop (*Bacopa monnieri*), green carpet weed, and frogfruit (*Phyla incisa*).

During the 8 years from the summer of 1973 to 1981, the bare dune field had migrated about 213 meters landward (west-northwest). Barring a severe

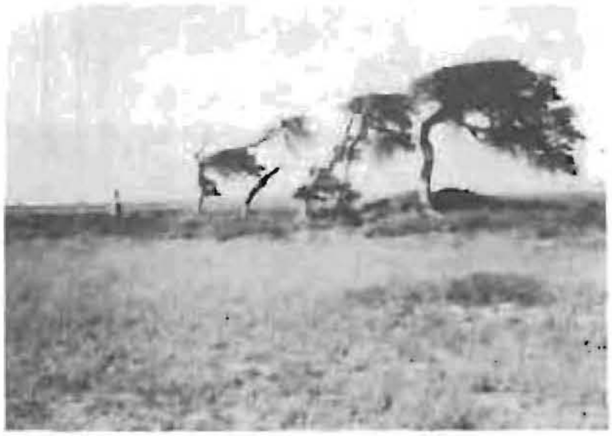
1969



1972



1974



1981

Figure 16. Stabilization of a midisland bare dune field between 1969 and 1981. Note the live oak mottes in dune field in 1969.

Aerial view of bare dune field in 1969.

Revegetation that occurred by 1974.

1981 photos of the same general area.

Figure 17. Stabilization of a midisland bare dune field between 1969 and 1981.

Table 11. Importance values[1] (IV) for plants occurring on a midisland area, recently vacated by a migrating bare dune field.

	Distance from Bare Dune Field (m)			
	0 - 76	76 - 152	152 - 229	229 - 305
Cynodon dactylon	5	190	135	4
Eragrostis oxylepis	8	376	82	144
Panicum oligosanthes	0	0	1	116
Paspalum monostachyum	0	0	10	426
Paspalum spp.	0	1	2	92
Schizachyrium scoparium	0	28	1219	1329
Cyperus spp.	2	22	199	8
Eleocharis albida	0	23	641	18
Eleocharis parvula	0	10	6	59
Fimbristylis spp.	115	0	9	40
Juncus scirpoidea	1	14	144	265
Scirpus americanus	0	0	16	0
Bacopa monnieri	0	61	183	8
Baptisia leucophaea	0	0	1	36
Cassia fasciculata	0	118	9	913
Conyza canadensis	0	0	0	9
Coreopsis tinctoria	0	5	1	0
Erigeron myrionactis	0	8	2	30
Heterotheca pilosa	0	0	1	105
Hydrocotyle bonariensis	0	0	1	0
Linum alatum	0	2	1	17
Mollugo verticellata	0	1	8	0
Oenothera drummondii	0	22	0	0
Polpremum procumbens	0	64	6	15
Phyla incisa	0	0	12	0
Sisyrinchium biforme	0	0	1	0
Vernonia texana	0	20	155	1
Vegetation Cover (percent)	3	24	42	56

[1] IV = product of percent frequency X percent coverage.

drought, pioneer plant species are colonizing to such an extent that in a relatively few years the large dune field that existed in the 1960's on the Laguna Madre side of Padre Island will disappear. This rapid revegetation is possible because the north end of Padre Island National Seashore is no longer grazed by livestock and recreational use is limited to managed areas.

V. CONCLUSIONS

Hurricane Allen's impact on north Padre Island dunes was confined primarily to eroding the face of both the natural and experimental dunes leaving vertical cliffs. It breached only one experimental dune, the 335-meter bitter panicum dune. During Hurricane Allen part of the eroded sand from the beach was transported farther inland around the ends of existing dunes or through breaches in dunes. Also, much of the beach sand was transported temporarily into the gulf. Apparently, the sand deposited in the gulf was quickly redeposited on the beach, as the cross-sectional surveys revealed a near-normal beach elevation 7 months after the storm.

The hurricane's impact on north Padre Island beaches appeared much less severe than previous major hurricanes, such as Hurricane Carla and Hurricane Beulah in the 1960's. This conclusion was reached because elevations in 1969 on the backshore, where the experimental dune plantings were made, were only 1.4 meters above MSL. Similar locations 7 months after Hurricane Allen had elevations of more than 1.5 meters above MSL.

Sand accumulating on the beach and foredune 199 meters (distance inland) continues to accumulate at about 11.5 cubic meters per linear meter of beach, which is near the rate reported by Dahl and Goen (1977) for the 1975-76 monitoring period. Both the natural and experimental dunes continue to widen 1.8 to 2.4 meters per year. The base widths of all the experimental dunes now exceed 30 meters (elevations 2.4 meters above MSL), which may not withstand the erosion attributed to Hurricane Carla in 1961 when the natural dunes of this width were destroyed. However, these experimental dunes would be more than adequate to withstand major hurricanes comparable to Hurricane Allen. Naturally formed dunes have basal widths more than 76 meters. Apparently the dune-width extension dune, with an initial 15-meter planting in 1969, followed in 1973 by another 15-meter planting seaward, can provide an effective barrier to hurricane erosion. This dune width is now 50 meters compared with only 30 to 40 meters for dunes resulting from a single planting.

Naturally forming dunes, such as the unplanted control area monitored, will require a 25-year storm-free interval to provide protection equivalent to the double width experimental dune.

Invasion of unplanted species into the experimental foredunes continues to be extremely slow due to the rapid sand accretion and plant vulnerability to salt spray. For example, the back (landward) dune of the dune-width extension planting (Table 9) had 10 species compared with essentially the planted species on the front (seaward) dune. The ground cover was much greater when protected from salt spray (80 percent versus 34 percent on the back and front dunes, respectively). This is further evident by noting the well-developed grassland landward of the foredunes. The ground cover averages 56 percent behind the experimental foredunes with 18 species commonly occurring. The unplanted control area did not have the protection of a well-developed foredune ridge, nor did it have the depression landward of the dune providing the mesic habitat favorable to the species more commonly found behind the dunes resulting from grass plantings. Only nine species were common and ground cover averaged only 17 percent. Because the foredune ridge was not well formed, the sand deposition was greater in this area and also covered much of the prehurricane vegetation.

A midisland bare dune field migrating toward Laguna Madre continues to move at about 27 meters annually. Although plant succession on beach foredunes occurs slowly, rapid plant succession is taking place here. Early colonizers are bermuda grass, red love grass, and species of *Juncus* and *Cyperus*. Species more indicative of a mature grassland, such as seacoast bluestem, soon follow. Apparently, this rapid successional advance is possible due to lack of cattle grazing, minimal recreational disturbance, reestablishment of beach foredunes, and the absence of salt spray. At the current rate of revegetation, this bare dune field should entirely disappear within a relatively few years.

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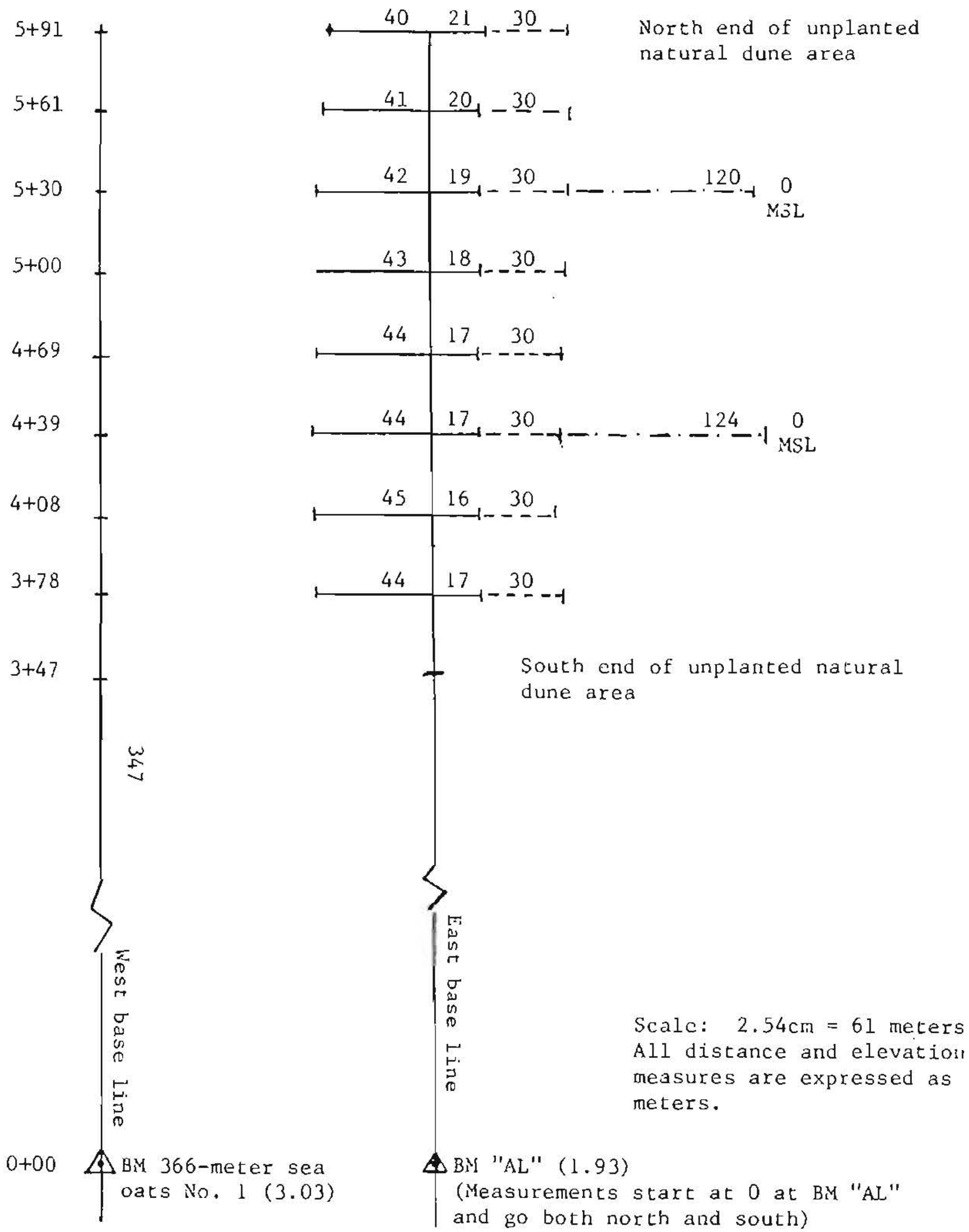
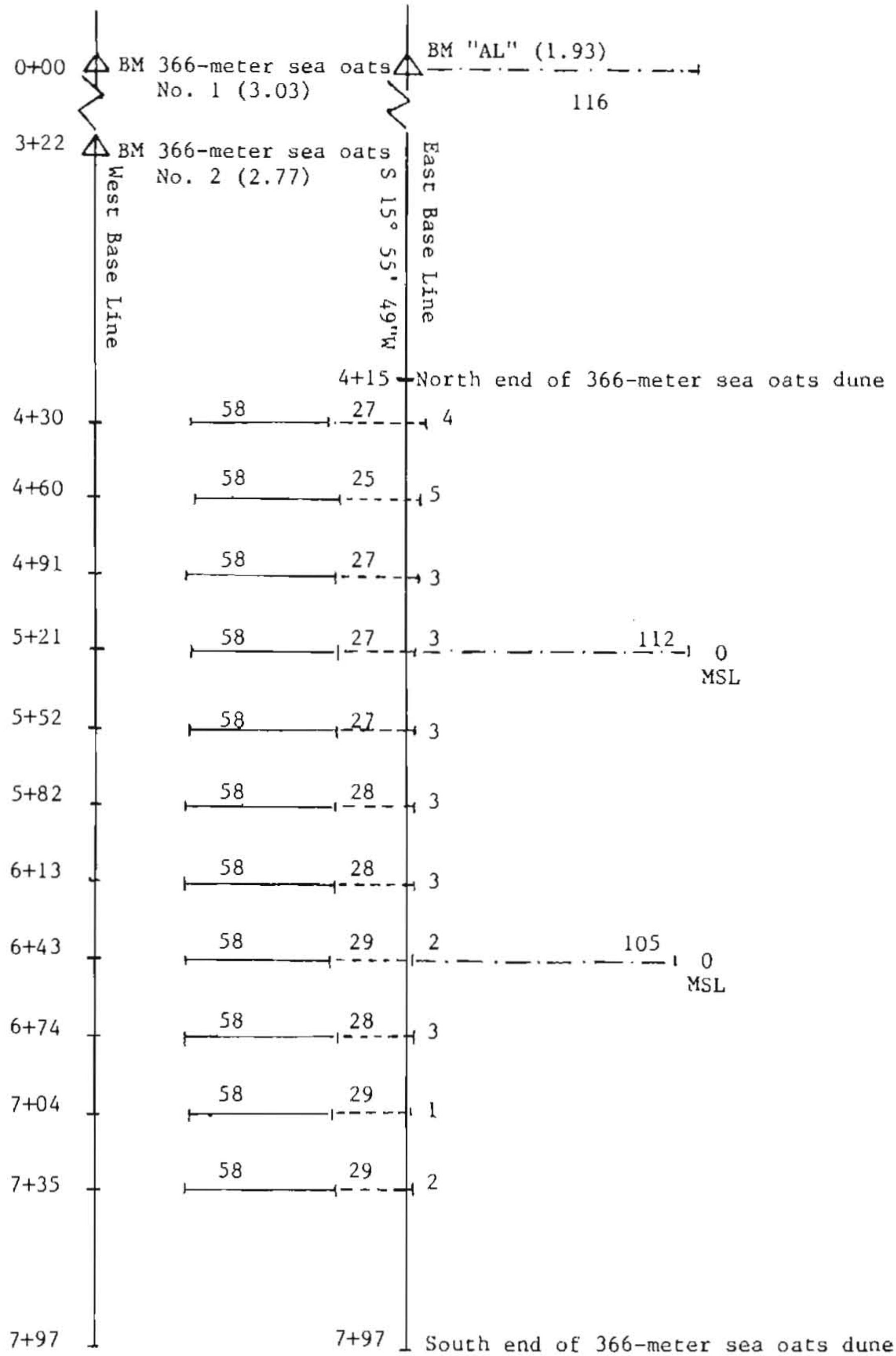
APPENDIX A

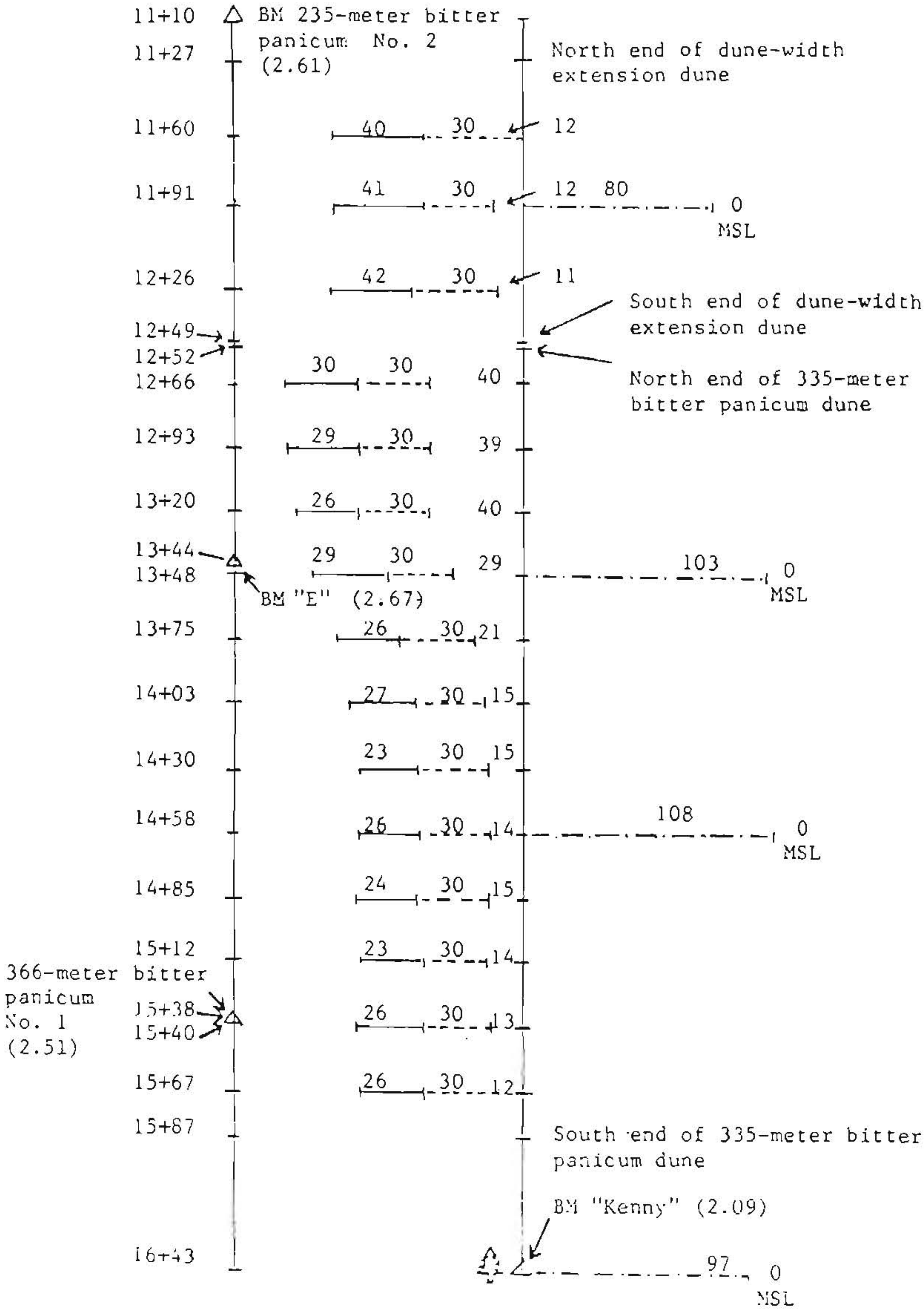
DETAILED DIAGRAM OF NORTH PADRE ISLAND STUDY PLOTS

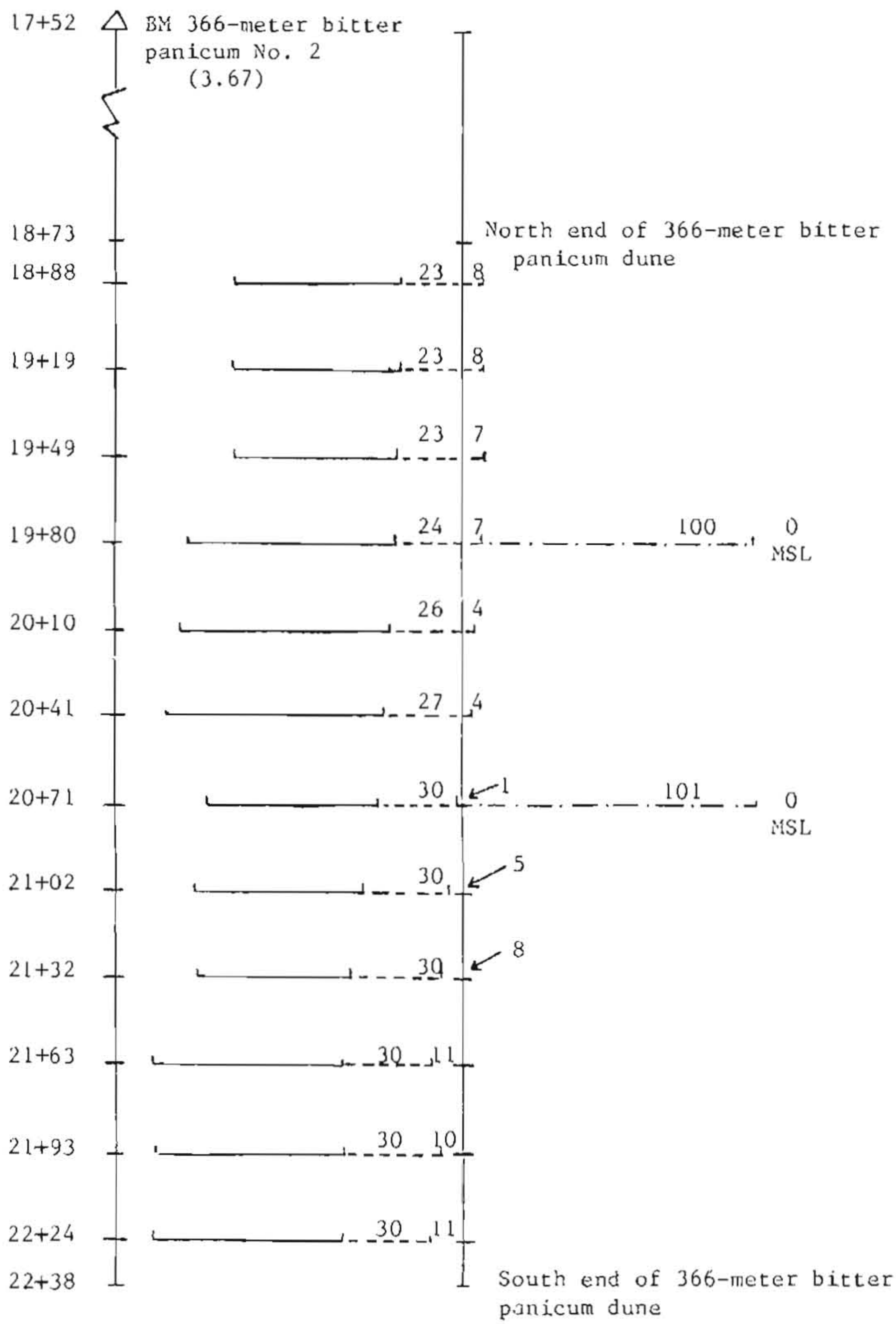
Because the cross-section locations are the same as the surveys made from 1975 to 1977, the same plot diagram is included as Appendix A as given in Miscellaneous Report No. 77-8 (Dahl and Goen, 1977).

Beach profiles are measured from 0 MSL to the East Base Line and the indicated number on each profile is the total distance to the East Base Line. The dashline shows the 30 meters seaward of the grass extension for each profile at the time of the 1976 survey. The solid line shows the length of the 1976 measured cross section across the unplanted area, the 366-meter sea oats dune, and the 366-meter bitter panicum dune. For the dune-width extension and the 335-meter bitter panicum dune, the solid line shows the 1976 distance to the back of the dune only.


5+91
5+61
5+30
5+00
4+69
4+39
4+08
3+78
3+47
0+00
40 21 30
41 20 30
42 19 30 120 0 MSL
43 18 30
44 17 30
44 17 30 124 0 MSL
45 16 30
44 17 30
North end of unplanted natural dune area
South end of unplanted natural dune area
347
West base line
East base line
Scale: 2.54cm = 61 meters
All distance and elevation measures are expressed as meters.
BM 366-meter sea oats No. 1 (3.03)
BM "AL" (1.93)
(Measurements start at 0 at BM "AL" and go both north and south)


0+00
BM 366-meter sea oats No. 1 (3.03)
BM "AL" (1.93)
116
3+22
BM 366-meter sea oats No. 2 (2.77)
West Base Line
S 15° 55' 49"W
East Base Line
4+15
North end of 366-meter sea oats dune
4+30
58
27
4
4+60
58
25
5
4+91
58
27
3
5+21
58
27
3
112
0
MSL
5+52
58
27
3
5+82
58
28
3
6+13
58
28
3
6+43
58
29
2
105
0
MSL
6+74
58
28
3
7+04
58
29
1
7+35
58
29
2
7+97
7+97
South end of 366-meter sea oats dune


11+10
BM 235-meter bitter panicum No. 2 (2.61)
11+27
North end of dune-width extension dune
11+60
40
30
12
11+91
41
30
12
80
0 MSL
12+26
42
30
11
South end of dune-width extension dune
12+49
12+52
12+66
30
30
40
North end of 335-meter bitter panicum dune
12+93
29
30
39
13+20
26
30
40
13+44
13+48
29
30
29
103
0 MSL
BM "E" (2.67)
13+75
26
30
21
14+03
27
30
15
14+30
23
30
15
14+58
26
30
14
108
0 MSL
14+85
24
30
15
15+12
23
30
14
366-meter bitter panicum No. 1 (2.51)
15+38
15+40
26
30
13
15+67
26
30
12
15+87
South end of 335-meter bitter panicum dune
BM "Kenny" (2.09)
16+43
97
0 MSL


17+52
BM 366-meter bitter panicum No. 2
(3.67)
18+73
North end of 366-meter bitter panicum dune
18+88
23
8
19+19
23
8
19+49
23
7
19+80
24
7
100
0
MSL
20+10
26
4
20+41
27
4
20+71
30
1
101
0
MSL
21+02
30
5
21+32
30
8
21+63
30
11
21+93
30
10
22+24
30
11
22+38
South end of 366-meter bitter panicum dune

APPENDIX B

VEGETATION FREQUENCY AND COVER ALONG FIVE TRANSECTS IN THE STUDY DUNES AND NEAR REMNANT LIVE OAK MOTTE NORTHWEST OF PADRE ISLAND RANGER STATION.

Table B-1. Percent frequency for foreslope of foredune.

	Unplanted Control			366-meter Sea Oats			Dune Width			335-meter Bitter Panicum			366-meter Bitter Panicum		
	75	76	81	75	76	81	75	76	81	75	76	81	75	76	81
Gramineae															
Cynodon dactylon															
Eragrostis oxylepis															
Eragrostis spectabilis															
Panicum amarum					8	13	100	98	95	88	93	78	100	100	92
Panicum amarulum															
Paspalum monostachyum															
Spartina patens		3	2			13									
Sporobolus virginicus		10													
Uniola paniculata	22	37	70	97	97	83		3	8	15	17	7	7	10	18
Cyperaceae															
Cyperus esculentus															
Eleocharis alida															
Eleocharis caribaea															
Eleocharis parvula															
Eleocharis spp.															
Fimbristylis caroliniana	8														
Fimbristylis castanea	12		2			2									
Scirpus americanus															
Leguminosae															
Baptisia leucophaca															
Cassia fasciculata															
Euphorbiaceae															
Croton capitatus															
Croton punctatus	32	42	8		5	40						10		2	8
Euphorbia ammanioides		10			2	3									2
Onagraceae															
Oenothera drummondii		20	5					2	3						
Umbelliferae															
Hydrocotyle bonariensis															
Primulaceae															
Samolus ebracteatus															
Gentianaceae															
Eustoma exaltatum															
Sabatia arenicola		5													
Convolvulaceae															
Ipomoea pes-caprae	10	5	5		8			2		13	12	2	2		
Ipomoea stolonifera	82	100	53	3								22			
Solanaceae															
Physalis viscosa						7			3		3				
Scrophulariaceae															
Bacopa monnieri		5													
Compositae															
Erigeron myrionactis															
Senecio riddellii															
Flaveria oppositifolia															
Verbenaceae															
Phyla incisa															

Table B-2. Percent cover for foreslope of foredune.

	Unplanted Control			366-meter Sea Oats			Dune Width			335-meter Bitter Panicum			366-meter Bitter Panicum		
	75	76	81	75	76	81	75	76	81	75	76	81	75	76	81
Gramineae															
Cynodon dactylon															
Eragrostis oxylepis															
Eragrostis spectabilis															
Panicum amarum					1	3	21	51	35	22	32	23	27	59	38
Panicum amarulum															
Paspalum monostachyum															
Spartina patens		T	T			1									
Sporobolus virginicus		T													
Uniola paniculata	1	4	7	12	27	16		T	T	1	2	1	T	2	3
Cyperaceae															
Cyperus esculentus															
Eleocharis alida															
Eleocharis caribaea															
Eleocharis parvula															
Eleocharis spp.															
Fimbristylis caroliniana	T														
Fimbristylis castanea	T		T			T									
Scirpus americanus															
Leguminosae															
Baptisia leucophaea															
Cassia fasciculata															
Euphorbiaceae															
Croton capitatus															
Croton punctatus	3	7	2		2	13						2		1	3
Euphorbia ammanioides		T			T	T									T
Onagraceae															
Oenothera drummondii	T	2	T					T	T						
Umbelliferae															
Hydrocotyle bonariensis															
Primulaceae															
Samolus ebracteatus															
Gentianaceae															
Eustoma exaltatum															
Sabatia arenicola		T													
Convolvulaceae															
Ipomoea pes-caprae	T	T	T		1			T		1	1	T	T		
Ipomoea stolonifera	5	13	6	T								4			
Solanaceae															
Physalis viscosa						2			T		T				
Scrophulariaceae															
Bacopa monnieri		T													
Compositae															
Erigeron myrionactis															
Senecio riddellii															
Flaveria oppositifolia															
Verbenaceae															
Phyla incisa									T						

Table B-3. Percent frequency for backslope of foredune.

	Unplanted Control			366-meter Sea Oats			Dune Width			335-meter Bitter Panicum			366-meter Bitter Panicum		
	75	76	81	75	76	81	75	76	81	75	76	81	75	76	81
Gramineae															
Cynodon dactylon															
Eragrostis oxylepis															
Eragrostis spectabilis															
Panicum amarum			5	32	35	30	72	78	73	85	83	67	98	98	63
Panicum amarulum															
Paspalum monostachyum		3													
Spartina patens		13	17		3	3	2	3							
Sporobolus virginicus	2	5	2						3						
Uniola paniculata	28	20	2	65	75	38	53	53		33	30	7		8	10
Cyperaceae															
Cyperus esculentus															
Eleocharis alida															
Eleocharis caribaea															
Eleocharis parvula															
Eleocharis spp.															
Fimbristylis caroliniana	2														
Fimbristylis castanea	5		35			2									
Scirpus americanus															
Leguminosae															
Baptisia leucophaea															
Cassia fasciculata	2	10					8	2		28	25				
Euphorbiaceae															
Croton capitatus															
Croton punctatus	28	50	7	2	5	10			5		5	2			3
Euphorbia ammanioides		3		22	7	5	2			17	8				3
Onagraceae															
Oenothera drummondii	12	37		8	18	2	2	2	8	18	25		5		2
Umbelliferae															
Hydrocotyle bonariensis															
Primulaceae															
Samolus ebracteatus															
Gentianaceae															
Eustoma exaltatum															
Sabatia arenicola		12		2									7		
Convolvulaceae															
Ipomoea pes-caprae	8	2		2	2						2				
Ipomoea stolonifera	88	98	60						8	7	21	20			
Solanaceae															
Physalis viscosa		2	2		3	20			3			12			5
Scrophulariaceae															
Bacopa monnieri		3													
Compositae															
Erigeron myrionactis		3			3										
Senecio riddellii															
Flaveria oppositifolia															
Verbenaceae															
Phyla incisa															

Table 8-4. Percent cover for backslope of foredune.

	Unplanted Control			366-meter Sea Oats			Dune Width			335-meter Bitter Panicum			366-meter Bitter Panicum		
	75	76	81	75	76	81	75	76	81	75	76	81	75	76	81
Gramineae															
Cynodon dactylon															
Eragrostis oxylepis															
Eragrostis spectabilis															
Panicum amarum			T	3	12	7	10	26	27	15	23	16	28	40	21
Panicum amarulum															
Paspalum monostachyum		T													
Spartina patens		1	3		T	T	T	T							
Sporobolus virginicus	T	T	T						T						
Uniola paniculata	3	1	T	4	20	10	6	13		2	5	1		1	1
Cyperaceae															
Cyperus esculentus															
Eleocharis alida															
Eleocharis caribaea															
Eleocharis parvula															
Eleocharis spp.															
Fimbristylis caroliniana	T														
Fimbristylis castanea	T		4			T									
Scirpus americanus															
Leguminosae															
Baptisia leucophaea															
Cassia fasciculata		4					1	T		4	9				
Euphorbiaceae															
Croton capitatus															
Croton punctatus	3	7	1	1	T	1			T		1	T			3
Euphorbia ammanioides		T		4	1	T	T			1	1				T
Onagraceae															
Oenothera drummondii	2	3		T	5	T	1	1	2	1	4		T		T
Umbelliferae															
Hydrocotyle bonariensis															
Primulaceae															
Samolus ebracteatus															
Gentianaceae															
Eustoma exaltatum															
Sabatia arenicola		1		T									T		
Convolvulaceae															
Ipomoea pes-caprae	1	T		T	T						T				
Ipomoea stolonifera	13	12	10						T	T	2	3			
Solanaceae															
Physalis viscosa		T	T		T	3			T			2			T
Scrophulariaceae															
Bacopa monnieri		T													
Compositae															
Erigeron myrionactis		T			1										
Senecio riddellii															
Flaveria oppositifolia															
Verbenaceae															
Phyla incisa															

Table B-5. Percent frequency for the back crest of the dune width extension dune.

	Unplanted Control			366-meter Sea Oats			Dune Width			335-meter Bitter Panicum			366-meter Bitter Panicum		
	75	76	81	75	76	81	75	76	81	75	76	81	75	76	81
Gramineae															
Cynodon dactylon															
Eragrostis oxylepis									5						
Eragrostis spectabilis									55						
Panicum amarum									72						
Panicum amarulum															
Paspalum monostachyum															
Spartina patens									2						
Sporobolus virginicus															
Uniola paniculata									68						
Cyperaceae															
Cyperus esculentus															
Eleocharis alida															
Eleocharis caribaea															
Eleocharis parvula															
Eleocharis spp.															
Fimbristylis caroliniana															
Fimbristylis castanea															
Scirpus americanus															
Leguminosae															
Baptisia leucophaea															
Cassia fasciculata									43						
Euphorbiaceae															
Croton capitatus															
Croton punctatus									12						
Euphorbia ammanioides									10						
Onagraceae															
Oenothera drummondii									53						
Umbelliferae															
Hydrocotyle bonariensis															
Primulaceae															
Samolus ebracteatus															
Gentianaceae															
Eustoma exaltatum															
Sabatia arenicola															
Convolvulaceae															
Ipomoea pes-caprae															
Ipomoea stolonifera									67						
Solanaceae															
Physalis viscosa									38						
Scrophulariaceae															
Bacopa monnieri															
Compositae															
Erigeron myrionactis									30						
Senecio riddellii															
Flaveria oppositifolia															
Verbenaceae															
Phyla incisa															

Table B-6. Percent cover for the back crest of the dune width extension dune.

	Unplanted Control			366-meter Sea Oats			Dune Width			335-meter Bitter Panicum			366-meter Bitter Panicum		
	75	76	81	75	76	81	75	76	81	75	76	81	75	76	81
Gramineae															
Cynodon dactylon															
Eragrostis oxylepis									T						
Eragrostis spectabilis									T						
Panicum amarum									11						
Panicum amarulum															
Paspalum monostachyum															
Spartina patens									3						
Sporobolus virginicus															
Uniola paniculata									12						
Cyperaceae															
Cyperus esculentus															
Eleocharis alida															
Eleocharis caribaea															
Eleocharis parvula															
Eleocharis spp.															
Fimbristylis caroliniana															
Fimbristylis castanea															
Scirpus americanus															
Leguminosae															
Baptisia leucophaea															
Cassia fasciculata									11						
Euphorbiaceae															
Croton capitatus															
Croton punctatus									3						
Euphorbia ammanioides									T						
Onagraceae															
Oenothera drummondii									7						
Umbelliferae															
Hydrocotyle bonariensis															
Primulaceae															
Samolus ebracteatus															
Gentianaceae															
Eustoma exaltatum															
Sabatia arenicola															
Convolvulaceae															
Ipomoea pes-caprae															
Ipomoea stolonifera									15						
Solanaceae															
Physalis viscosa									5						
Scrophulariaceae															
Bacopa monnieri															
Compositae															
Erigeron myrionactis									6						
Senecio riddellii															
Flaveria oppositifolia															
Verbenaceae															
Phyla incisa															

Table B-7. Percent frequency for area 7.6 meters bayward of foredune.

	Unplanted Control			366-meter Sea Oats			Dune Width			335-meter Bitter Panicum			366-meter Bitter Panicum		
	75	76	81	75	76	81	75	76	81	75	76	81	75	76	81
Gramineae															
Cynodon dactylon		2		35	5										15
Eragrostis oxylepis						18			18			33			33
Eragrostis spectabilis						3			5			8			
Panicum amarum			10	50	58	68	30	15	38	38	55	63	48	48	65
Panicum amarulum		3							8				3		
Paspalum monostachyum		7	3	3		68						13			
Spartina patens			13			33									
Sporobolus virginicus	10	12	3	43	63	45	5	5	45	8	3	23	3	10	8
Uniola paniculata	5	7			23		15	18	13	20	10	15	28	23	20
Cyperaceae															
Cyperus esculentus							3	3	3						
Eleocharis alida		3			35										
Eleocharis caribaca								40	3		5	5			
Eleocharis parvula					30										
Eleocharis spp.				35											
Fimbristylis caroliniana	40			8		5	5	3	3			25			2
Fimbristylis castanea	13	5	65	78	40	45	75	80	48	40	53	40	18	58	23
Scirpus americanus			5			15									2
Leguminosae															
Baptisia leucophaea											3				
Cassia fasciculata		17					3	5	18	8	25	50	3	5	33
Euphorbiaceae															
Croton capitatus															
Croton punctatus	35	30	8		3		5	3		8	5	5	5		2
Euphorbia ammannioides	10	3		8	3				5			3			
Onagraceae															
Oenothera drummondii	40	42		8	13		20	23	33	50	53	40	33	23	30
Umbelliferae															
Hydrocotyle bonariensis		3		55	85	55	15	20	40	5	20	18		3	30
Primulaceae															
Samolus ebracteatus	8	3		75	20	75		3	40	3	13	40		23	55
Gentianaceae															
Eustoma exaltatum		3		25		13			3	8			3		
Sabatia arenicola		38		10	25	70	5	30	68	20	20	40	40	18	55
Convolvulaceae															
Ipomoea pes-caprae	5	2		15	3					5	3		10	5	
Ipomoea stolonifera	98	95	33			3	23	68	43	28	43	33	8	28	8
Solanaceae															
Physalis viscosa			3	3	8	3			3			10		3	13
Scrophulariaceae															
Bacopa monnieri	3	17		70	25		3	13		5	5		10	28	2
Compositae															
Erigeron myrionactis		30			3	23			63	3		48		13	45
Senecio riddellii															
Flaveria oppositifolia						42			38			15			
Verbenaceae															
Phyla incisa		3			8							8			

Table B-8. Percent cover for area 7.6-meters bayward of foredune.

	Unplanted Control			366-meter Sea Oats			Dune Width			335-meter Bitter Panicum			366-meter Bitter Panicum		
	75	76	81	75	76	81	75	76	81	75	76	81	75	76	81
Gramineae															
Cynodon dactylon		T		2	T										2
Eragrostis oxylepis						2			T			1			3
Eragrostis spectabilis						T			T			T			
Panicum amarum			2	5	5	13	5	1	5	5	7	9	6	5	8
Panicum amarulum		1							2				2		
Paspalum monostachyum		1	T	T		6						1			
Spartina patens			1			13									
Sporobolus virginicus	T	T	T	2	6	4	T	T	4	T	T	2	T	1	T
Uniola paniculata	T	T			5		2	3	3	3	2	1	5	7	5
Cyperaceae															
Cyperus esculentus							T	T	T						
Eleocharis alida		T			2										
Eleocharis caribaea								T	T		1	T			
Eleocharis parvula					2										
Eleocharis spp.				T											
Fimbristylis caroliniana	1			T		T	T	T	T			2			2
Fimbristylis castanea	2	T	3	5	4	3	2	4	2	2	6	2	T	4	T
Scirpus americanus			T			T									T
Leguminosae															
Baptisia leucophaea											T				
Cassia fasciculata		3					T	1	3	T	11	19	T	1	13
Euphorbiaceae															
Croton capitatus															
Croton punctatus	4	1	T		T		T	T		T	T	2	T		T
Euphorbia ammannioides	T	T		1	T				T			T			
Onagraceae															
Oenothera drummondii	5	3		T	3		3	2	3	2	4	4	2	1	5
Umbelliferae															
Hydrocotyle bonariensis		T		5	4	2	2	1	3	1	2	2		T	2
Primulaceae															
Samolus ebracteatus	T	T		1	1	7		T	7	T	3	6		T	7
Gentianaceae															
Eustoma exaltatum		T		T		T			T	T			T		
Sabatia arenicola		1		T	T	2	T	1	5	T	T	1	T	1	2
Convolvulaceae															
Ipomoea pes-caprae	1	T		1	T					T	T		T	T	
Ipomoea stolonifera	12	9	3			T	1	5	3	3	3	2	1	3	T
Solanaceae															
Physalis viscosa			T	T	1	T			T			T		T	1
Scrophulariaceae															
Bacopa monnieri	T	3		3	1		T	T		T	T		T	1	T
Compositae															
Erigeron myrionactis		2			T	T			7	T		5		1	4
Senecio riddellii															
Flaveria oppositifolia						3			5			T			
Verbenaceae															
Phyla incisa					2										

Table B-9. Percent frequency for area 38.1-meters bayward of foredune.

	Unplanted Control			366-meter Sea Oats			Dune Width			335-meter Bitter Panicum			366-meter Bitter Panicum		
	75	76	81	75	76	81	75	76	81	75	76	81	75	76	81
Gramineae															
Cynodon dactylon	3	2		18	3						3	23			10
Eragrostis oxylepis						20			20			23			25
Eragrostis spectabilis						5			28			23			
Panicum amarum			3	13	30	48	5		35	25	5	35	3	5	18
Panicum amarulum				30	8	5		8							2
Paspalum monostachyum				25	40	28						3			
Spartina patens					5	18							3	3	8
Sporobolus virginicus		5		75	63	20	25	38	40	23	15			3	
Uniola paniculata				25	20	10	23	28	45	20	30	30	48	60	53
Cyperaceae															
Cyperus esculentus															
Eleocharis alida					15			10							
Eleocharis caribaea					28						33			18	
Eleocharis parvula		3						5		3				10	30
Eleocharis spp.				18					3			8			
Fimbristylis caroliniana	15	2		35	3	5	30		43	5		20	8		35
Fimbristylis castanea	23	2	45	68	45	38	85	70	53	45	85	45	35	50	48
Scirpus americanus			15			43			15			8			
Leguminosae															
Baptisia leucophaea															
Cassia fasciculata	5	27		5	5	13	15	25	63	25	20	48	3	15	68
Euphorbiaceae															
Croton capitatus							3								
Croton punctatus	43	48	3	10	5	3	10	5		10			13	8	
Euphorbia ammanioides		3		3	5	3		3							2
Onagraceae															
Oenothera drummondii	40	67		45	55	8	80	65	38	45	40	53	45	58	58
Umbelliferae															
Hydrocotyle bonariensis	8	2		73	45	58			23	5	25	33			10
Primulaceae															
Samolus ebracteatus		3		18	33	28	10	38	70	13	23	28		3	38
Gentianaceae															
Eustoma exaltatum		20		20		15	26	3	15	20	10			3	
Sabatia arenicola	3	30		28	18	25	65	30	75	15	20	28	20	50	53
Convolvulaceae															
Ipomoea pes-caprae	13	3		8	3			5		23	3		30	28	15
Ipomoea stolonifera	53	95	40	13	13	5	75	75	15	5	3	30	3	8	5
Solanaceae															
Physalis viscosa		2			5				8		3	8			15
Scrophulariaceae															
Bacopa monnieri	3	7		28	5		28	5		10	10		10	10	
Compositae															
Erigeron myrionactis	3	13		18	5	35	10	15	80	10	25	28		8	58
Senecio riddellii															
Flaveria oppositifolia						35			58			23			
Verbenaceae															
Phyla incisa									3			3			

Table B-10. Percent cover for area 38.1-meters bayward of foredune.

	Unplanted Control			366-meter Sea Oats			Dune Width			335-meter Bitter Panicum			366-meter Bitter Panicum		
	75	76	81	75	76	81	75	76	81	75	76	81	75	76	81
Gramineae															
Cynodon dactylon	T	T		T	T						T	3			T
Eragrostis oxylepis						3			2			3			1
Eragrostis spectabilis						T			5			3			
Panicum amarum			T	T	2	10	1		3	1	T	3	T	T	2
Panicum amarulum				3	3	T		1							T
Paspalum monostachyum				2	5	4						T			
Spartina patens					T	3							T	T	T
Sporobolus virginicus		T		3	5	T	T	1	3	1	1			T	
Uniola paniculata				2	3	4	5	8	5	2	7	7	6	6	10
Cyperaceae															
Cyperus esculentus															
Eleocharis alida					T			1							
Eleocharis caribaea					3						T			T	
Eleocharis parvula		T						T		1				T	T
Eleocharis spp.				1					T			T			T
Fimbristylis caroliniana	1	T		1	T	T	1		1	T		1	1		2
Fimbristylis castanea	T	T	4	4	3	5	4	9	2	2	6	2	T	2	2
Scirpus americanus			2			8			2			T			
Leguminosae															
Baptisia leucophaea															
Cassia fasciculata		8		1	1	2	1	6	10	5	1	16	T	1	14
Euphorbiaceae															
Croton capitatus							T								
Croton punctatus	7	6	T	1	T	T	T	1		2			1	1	
Euphorbia ammanioides		T		T	T	T		T							T
Onagraceae															
Oenothera drummondii	4	4		6	3	T	7	9	1	3	2	6	3	3	3
Umbelliferae															
Hydrocotyle bonariensis	T	T		4	1	10			T	T	T	4			T
Primulaceae															
Samolus ebracteatus		T		T	1	3	T	9	5	T	1	3		T	2
Gentianaceae															
Eustoma exaltatum		1		T		T	T	T	T	T	T			T	
Sabatia arenicola	T	1		T	T	2	1	2	2	T	T	T	T	1	2
Convolvulaceae															
Ipomoea pes-caprae	2	T		T	T			T		T	T		2	1	T
Ipomoea stolonifera	6	8	10	T	T	T	6	11	T	1	T	4	T	T	T
Solanaceae															
Physalis viscosa		T			T				T		T	2			2
Scrophulariaceae															
Bacopa monnieri	T	T		1	T		1	T		1	T		T	T	
Compositae															
Erigeron myrionactis	1	T		1	T	2	T	1	6	1	2	3		T	4
Senecio riddellii															
Flaveria oppositifolia						2			5			1			
Verbenaceae															
Phyla incisa									T			T			

Table B-11. Percent frequency for area 68.6-meters bayward of foredune.

	Unplanted Control			366-meter Sea Oats			Dune Width			335-meter Bitter Panicum			366-meter Bitter Panicum		
	75	76	81	75	76	81	75	76	81	75	76	81	75	76	81
Gramineae															
Cynodon dactylon				50	13		20	5	3						5
Eragrostis oxylepis						8			10			58			45
Eragrostis spectabilis			8			3						13			43
Panicum amarum			3	15	20	18		3	18		13	20	3		13
Panicum amarulum					13	13			20			8		8	3
Paspalum monostachyum			3	8	35	50			15	3	3	45			13
Spartina patens			5		3	20				5					
Sporobolus virginicus			3	75	40	28	65		90	5	18	23	10	10	10
Uniola paniculata				3	8	3	20		8	45	58	30	15	30	28
Cyperaceae															
Cyperus esculentus		8													
Eleocharis alida		8			13								3		
Eleocharis caribaea		20			38			33			25				
Eleocharis parvula		8			3			18							
Eleocharis spp.				15		15			5			15			18
Fimbristylis caroliniana	23	5	3	33		15	15		5	30			63		2
Fimbriatylis castanea	8			88	35	8	88	80	30	43	83	33	30	33	48
Scirpus americanus			5			55			63			38			18
Leguminosae															
Baptisia leucophaea					3										
Cassia fasciculata		20	13	8	35	18		10		45	43	65	13	48	58
Euphorbiaceae															
Croton capitatus				3					5			8			
Croton punctatus	58	43	10	8						15		8	20	15	3
Euphorbia ammanioides		3		3	3			3			3				
Onagraceae															
Oenothera drummondii	48	45	23	28	38	5	43	23	10	73	83	53	65	65	58
Umbelliferae															
Hydrocotyle bonariensis		10	13	75	58	58	8	33	3	20	18	33			3
Primulaceae															
Samolus ebracteatus		3		13	43	43	28	48	80		28	58	5	28	35
Gentianaceae															
Eustoma exaltatum		20		55	5	20	28	3	13	8	3	20		3	8
Sabatia arenicola		28		48	40	30	43	5	73		23	55	12	28	68
Convolvulaceae															
Ipomoea pes-caprae	5	25							3	3			8	5	8
Ipomoea stolonifera	55	73	60	8	8		28	23	10	13	8	18	4	28	8
Solanaceae															
Physalis viscosa			8	20	3				5	5	15	8			10
Scrophulariaceae															
Bacopa monnieri		13		53	5		55		3	8	13			10	
Compositae															
Erigeron myrionactis		28			20	48	43	10	40	10	60	63	8	30	70
Senecio riddellii															
Flaveria oppositifolia						45			90			55			18
Verbenaceae															
Phyla incisa		8			10	10				3		8			2

Table B-12. Percent cover for area 68.6 meters bayward of foredune.

	Unplanted Control			366-meter Sea Oats			Dune Width			335-meter Bitter Panicum			366-meter Bitter Panicum		
	75	76	81	75	76	81	75	76	81	75	76	81	75	76	81
Gramineae															
Cynodon dactylon				1	1		T	T	T						T
Eragrostis oxylepis						T			T			5			4
Eragrostis spectabilis			2			T						2			4
Panicum amarum			T	1	1	3		T	3		1	T	T		2
Panicum amarulum					3	10			4			T		T	T
Paspalum monostachyum			T	T	5	4			T	T	T	11			2
Spartina patens			T		T	4				T					
Sporobolus virginicus			T	5	2	T	2		9	T	T	1	T	T	T
Uniola paniculata				T	1	T	T		1	5	11	3	2	4	3
Cyperaceae															
Cyperus esculentus		T													
Eleocharis alida		T			1								T		
Eleocharis caribaea		1			2			1			T				
Eleocharis parvula		T			1			1							
Eleocharis spp.				T		T			T			T			T
Fimbristylis caroliniana	T	T	T	2		9	T		T	1			7		T
Fimbristylis castanea	T			8	2	T	8	7	1	2	8	4	1	4	3
Scirpus americanus			T			6			9			3			T
Leguminosae															
Baptisia leucophaea					T										
Cassia fasciculata		3	4	3	3	2		T		13	5	9	5	5	5
Euphorbiaceae															
Croton capitatus				T					T			T			
Croton punctatus	7	5	1	T						T		T	1	1	T
Euphorbia ammanioides		T		T	T			T		3	T				
Onagraceae															
Oenothera drummondii	6	2	4	1	5	T	5	1	T	5	8	4	6	7	3
Umbelliferae															
Hydrocotyle bonariensis		1	3	6	1	5	T	1	T	T	T	2			T
Primulaceae															
Samolus ebracteatus		T		T	4	2	1	2	4		T	3	T	3	2
Gentianaceae															
Eustoma exaltatum		1		1	T	T	1	T	T	T	T	T		T	T
Sabatia arenicola		1		1	1	T	1	T	2		T	2	T	1	1
Convolvulaceae															
Ipomoea pes-caprae	1	2							T	T			T	T	T
Ipomoea stolonifera	7	7	7	1	T		T	T	1	2	T	1	2	1	T
Solanaceae															
Physalis viscosa			1	1	T				T	T	1	T			T
Scrophulariaceae															
Bacopa monnieri		2		5	T		1		T	1	T			T	
Compositae															
Erigeron myrionactis		1			1	3	1	T	1	T	3	6	1	2	8
Senecio riddellii															
Flaveria oppositifolia						4			8			4			2
Verbenaceae															
Phyla incisa		1	T		1	T				T		T			T

Table B-13. Vegetation frequency and cover (percent) near remnant live oak motte northwest of Padre Island Ranger Station.

	Frequency		Cover	
	North of oak motte	South of oak motte	North of oak motte	South of oak motte
Graminea				
Paspalum monostachyum	17	23	3	3
Cynodon dactylon	46	29	1	1
Eragrostis oxylepsis	49	31	2	3
Schizachyrium scoparium var littoralis	54	54	T	9
Chloris spp.	14	17	T	T
Panicum spp.	14	20	T	T
Cyperacea				
Eleocharis parvula	9	17	T	1
Elocharis alida	20	23	1	4
Cyprus esculentus	34	23	1	1
Fimbristylis castanea	26	11	2	T
Fimbristylis caroliniana		6		T
Scirpus americanus		9		T
Juncaceae				
Juncus scirpoides	51	26	T	1
Leguiminosae				
Baptisia leucophaea	3	6	T	T
Cassia fasiculata	23	27	T	5
Onagraceae				
Oenothera drummondii	6		T	
Umbelliferae				
Hydrocotyle bonariensis	3		T	
Scrophulariaceae				
Bacopa monnieri		34		T
Loganiaceae				
Polypremum procumbems	23	31	T	T
Compositae				
Erigeron myrionactis	6	20	T	T
Vernonia texana	20	20	T	1
Coreopsis tinctoria	6	9	T	T
Heterotheca pilosa	23	17	T	T
Conyza canadensis	3		T	
Verbenaceae				
Phyla incisa		9		T
Iridaceae				
Sisyrinchium biforme	3		T	
Linaceae				
Linum alatum	3	20	T	T

Table B-13. Vegetation frequency and cover (percent) near remnant live oak motte northwest of Padre Island Ranger Station.

	Frequency		Cover	
	North of oak motte	South of oak motte	North of oak motte	South of oak motte
Gramineae				
Paspalum monostachyum	17	23	3	3
Cynodon dactylon	46	29	1	1
Eragrostis oxylepis	49	31	2	3
Schizachyrium scoparium var littoralis	54	54	T	9
Chloris spp.	14	17	T	T
Panicum spp.	14	20	T	T
Cyperaceae				
Eleocharis parvula	9	17	T	1
Elocharis albida	20	23	1	4
Cyperus esculentus	34	23	1	1
Fimbristylis castanea	26	11	2	T
Fimbristylis caroliniana		6		T
Scirpus americanus		9		T
Juncaceae				
Juncus scirpoides	51	26	T	1
Leguiminosae				
Baptisia leucophaea	3	6	T	T
Cassia fasciculata	23	27	T	5
Onagraceae				
Oenothera drummondii	6		T	
Umbelliferae				
Hydrocotyle bonariensis	3		T	
Scrophulariaceae				
Bacopa monnieri		34		T
Loganiaceae				
Polypremum procumbens	23	31	T	T
Compositae				
Erigeron myrionactis	6	20	T	T
Vernonia texana	20	20	T	1
Coreopsis tinctoria	6	9	T	T
Heterotheca pilosa	23	17	T	T
Conyza canadensis	3		T	
Verbenaceae				
Phyla incisa		9		T
Iridaceae				
Sisyrinchium biforme	3		T	
Linaceae				
Linum alatum	3	20	T	T

Dahl, B.E.
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ANALYSIS METHOD FOR STUDYING SEDIMENTATION PATTERNS

By J. Richard Weggel,[1] M. ASCE

INTRODUCTION

It is often necessary to quantify changes in water depth brought about by either sedimentation or scour in enclosed or semi-enclosed water bodies. For example, historical sedimentation patterns can be used to estimate future patterns and then used to determine future dredging requirements for river, harbor, and estuary navigation channels. Usually, depth changes that occur between two surveys must be quantified. One method of quantifying shoaling patterns is to superimpose charts from two surveys and construct contour lines of the differences in bottom elevation. This graphically shows where shoaling and scour have occurred. Contour lines constructed in this way are useful for identifying areas in navigation channels, harbors, or estuaries where dredging is likely to be needed.

ANALYSIS METHOD

Another method of analysis is presented herein to help identify the depths in which sedimentation occurs rather than the location. The area under study was Mill Cove, a semi-enclosed basin adjacent to the St. Johns River in Jacksonville Harbor, Florida. Historical changes in the location of the main navigation channel and the disposal of dredged material adjacent to the main channel in the St. Johns River resulted in flow pattern changes and, consequently, in sedimentation pattern changes within the cove. Mill Cove was once a part of the navigation channel of the St. Johns River; however, improvements to the navigation channel resulted in Mill Cove being essentially cut off from the present navigation channel. Periodic dredging of the channel and the build-up of spoil islands adjacent to it further cut off the cove from the main flow of the St. Johns River. Figure 1 shows the condition of the cove in 1974. In about 1950 the Corps of Engineers constructed a weir structure in the entrance at the northeast end of the cove to control tidal currents emanating from the cove and moving transverse to the navigation channel.

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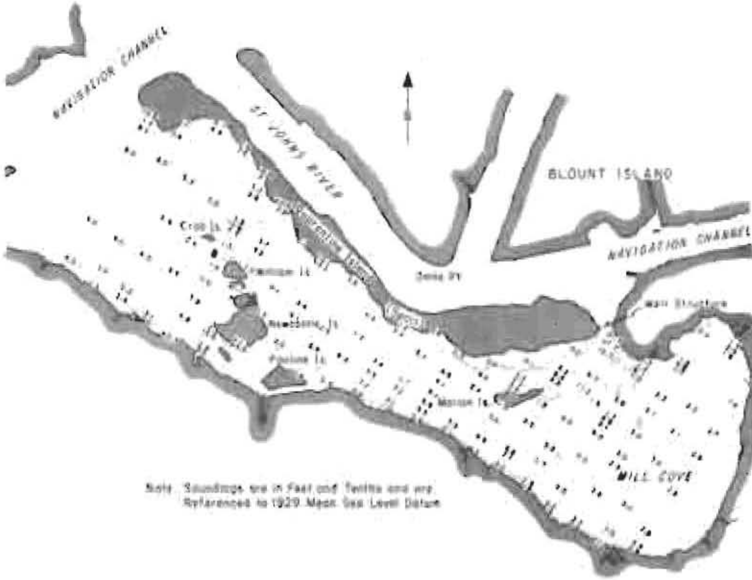

FIG. 1.—Bathymetry of Mill Cove, Jacksonville Harbor, Florida in 1974. (Soundings in Feet; 1 ft = 0.305 m)

These currents were deemed to pose a navigation hazard. The weir structure is approximately 150 ft (45.7 m) wide at its base and has a sill elevation at −12.0 ft (−3.66 m) below MLW.

The Corps of Engineers has been studying the feasibility of improving the circulation within Mill Cove and enhancing its recreational use. A major factor affecting land values along the southern shore of the cove is the shoaling rate in the shallow water along the shoreline; significant economic benefits accrue to the project if this shoaling rate can be reduced or even reversed. The prevention of further mud flat and marsh development adjacent to the south shore is a major purpose of the Corps plan. One alternative under study is removal of the weir structure at the northeast end and deepening of the channel at the west end of the cove to improve the tidal exchange between the river and cove; however, it is not certain that removal of the weir will decrease nearshore, shallow water shoaling rates. If the shoaling rates in only the deeper portions of the cove are decreased by weir removal, benefits associated with improved property values will not be realized. It was therefore necessary to determine the depths in which shoaling occurred rather than just simply the amount of shoaling.

Six bathymetric surveys, the earliest dating back to 1855, were available for Mill Cove. Four of the surveys—in 1855, 1894, 1909, and 1934—predate weir construction, while two surveys—in 1974 and 1977—postdate weir construction.

To determine the depths in which shoaling was taking place, the area of the cove having a water depth below a given depth was plotted as a function of that given depth. Figure 2 shows schematically how data

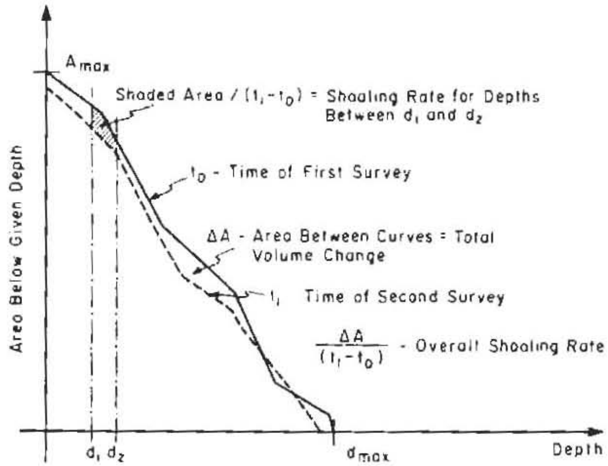

FIG. 2.—Schematic of Plot of Basin Area below Given Depth versus Depth

from two surveys, separated in time, for the same body of water might look. In general, the curve of area vs. depth is a monotonically decreasing function, i.e. smaller areas are at deeper depths. This type of curve is frequently used to describe the capacity of a reservoir as a function of water level behind a dam and, when used to describe the depths of the oceans, is termed a hypsographic curve. This curve can be constructed by planimetering bathymetric contours or, if soundings are fairly uniformly distributed over the basin under consideration, depth values can be ranked and the percentage of the basin's area below a given depth determined. In the present application, the difference between two such curves is used to describe changes in depth that occur with time. The intercept on the ordinate is the total area of the basin and the intercept on the abcissa is the maximum depth. The area between two such curves represents the total amount (volume) of shoaling or scour that has occurred between the two surveys and, when divided by the time between the two surveys, is the average shoaling or scour rate (volume/unit time). The shoaling or scour rate for a given range of water depths can also be

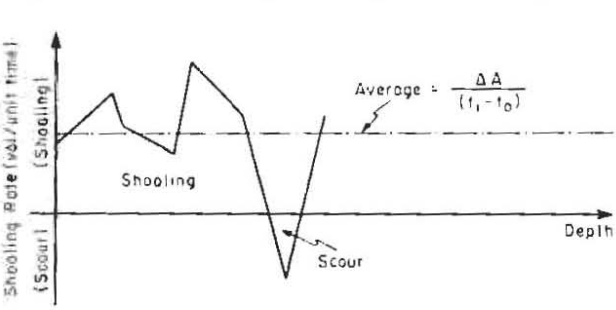

FIG. 3.—Schematic of Shoaling and Scour Rates as Function of Depth (Derived from Fig. 2)

determined by finding the area bounded by the two curves and the two given water depths. If the two curves cross, it indicates that scour is occurring in some depths while shoaling is occurring in others. Shoaling or scour rates can be determined as a function of depth by plotting the difference between the two curves as a function of depth. (See Fig. 3.)

The actual data from the Mill Cove surveys are shown in Fig. 4. The curves show that shoaling occurred most rapidly in deeper parts of the cove and that scour occurred in some of the shallower parts. The curves appear in two groups, those curves for surveys in 1934 and earlier and those for 1974 and 1977. The 1894 survey is believed to be anomalous since a large amount of dredging was done shortly before the survey. This would explain the generally greater depths in the 1894 survey. The surveys for 1934 and earlier suggest that the cove is tending toward an equilibrium depth close to 6 ft (1.83 m) since depths greater than 6 ft appear to be shoaling while shallower depths appear to be scouring. The 1974 and 1977 surveys suggest a shallower equilibrium depth, close to 3 ft (0.91 m). Again, depths greater than this equilibrium depth are shoaling while shallower depths are scouring. While it is not certain, the two groups of curves suggest that construction of the flow control weir at the east end of Mill Cove has altered the flow patterns enough to change the sedimentation patterns and, therefore, the equilibrium depth. The absence of surveys immediately before and after weir construction makes it difficult to be certain of this interpretation. However, if this interpretation is correct, improving the circulation in Mill Cove by re-

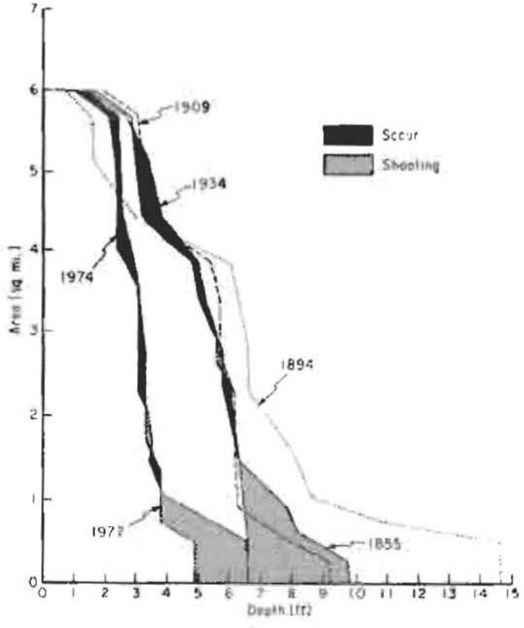

FIG. 4.—Mill Cove Data for 1855, 1894, 1909, 1934, 1974, and 1977: Cove Area below Given Depth versus Depth. (1 ft = 0.305 m; 1 sq mile = 2.59 km²)

moving the weir may reverse the present trend and result in an overall deepening of the cove. This assumes that the threshold velocities required to initiate sediment transport will be exceeded when the circulation is improved. The deepest parts of the cove are expected to continue shoaling.

CONCLUSIONS

Comparison of two area vs. depth curves as previously described provides a method for determining the depths in which sedimentation and scour are occurring. The area between two such curves divided by the time difference between the two surveys for which the curves are constructed will give the shoaling or scour rate. Shoaling or scour rates can be determined as a function of water depth simply by taking the difference between the ordinates of the two curves divided by the time between the two surveys for any given water depth. This analysis can provide insight into sedimentation trends for enclosed or semi-enclosed water bodies that routine plots of bathymetric changes cannot.

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MOVABLE-BED MODELING LAW FOR COASTAL DUNE EROSION

By Steven A. Hughes,[1] M. ASCE

ABSTRACT: Similitude relationships for the physical modeling of coastal dune erosion in movable-bed models are developed based on consideration of the inertial forces, represented by the turbulent shear stress, and the gravity force in the nearly horizontal direction of the principal flow. This results in a dynamic scaling relationship for a distorted model. By requiring similarity of the dimensionless fall velocity parameter between the prototype and model and combining this criterion with the dynamic scaling, the necessary model distortion is derived. The main difference between these relationships and previous modeling laws is in the hydrological time scaling which is also distorted. The derived similitude relationships were verified by reasonable reproduction of the dune erosion which occurred during a prototype event. The model tests included a time-dependent storm surge hydrograph and an increasing wave height as the storm progressed. It is concluded that the model verification has been successful in at least one instance where prototype data were available, but further verification is desirable as prototype data become available.

INTRODUCTION

Many hydraulic problems are fairly simple in nature and can be solved adequately by analytical methods to a reasonable degree of accuracy. However, there are many more cases where the problem being considered is far too complex to be handled analytically. In these cases, simple approximations are insufficient and other means of obtaining engineering solutions are necessary. This is when small-scale modeling of a hydraulic phenomenon can prove beneficial by aiding in the development of a physical solution or by helping us to arrive at parametric relationships which can aid in our understanding of the hydraulic process under consideration.

Of all the hydraulic engineering models which can be performed, movable-bed scale-model investigations of coastal erosion and coastal sediment transport phenomena are probably the most difficult. In fact, so many different model laws have been proposed that modeling of this type should be considered more of an art than a science! However, by carefully identifying the major forces involved, it should be possible to derive a model law which can be verified and which will provide reasonable, quantitative results.

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This paper presents the derivation of a distorted, movable-bed modeling law for use in small-scale investigations of coastal dune erosion during severe storms. The modeling law is based on consideration of the inertial forces represented by the turbulent shear stress and the gravity force in the nearly horizontal direction of the principal flow. The resulting dynamic similitude criterion is then combined with a beach profile similarity criterion, based on preservation of the dimensionless fall velocity parameter, to form the complete set of modeling relationships. While similar to previous modeling laws, the derived relationships differ primarily in the hydrological time scaling.

Verification of the small-scale similitude relationships involves the reproduction, at small scale, of actual prototype events. However, in the case of coastal dune erosion during severe storms, scant data are available on which to base these verification tests. This paper describes the successful small-scale reproduction of the dune erosion in the Florida Panhandle caused by the 1975 Hurricane Eloise. While further verification of the model laws, using different storm events is desirable, the results described herein are at least encouraging.

The second phase of the study used the derived modeling relationships to conduct a series of small-scale dune erosion experiments. These results yielded an improved procedure for estimating coastal dune erosion for any given set of storm parameters. This phase is examined in Hughes and Chiu (8).

Previous Scale-Model Relationships

Numerous papers have been written proposing similitude relationships for movable-bed coastal models. Hudson, et al. (7) provide a rather complete bibliography of the subject. These relationships range from those which were derived solely by theoretical considerations to those which were established on a strictly empirical foundation. In each case, the relationship is assumed valid for a given set of specific flow characteristics.

Perhaps the most thorough investigation using known relationships of beach processes to determine the proper scaling law for coastal movable-bed models was that of Fan and LeMehaute (5). Their result was a table containing eight proposed scaling relationships, each a combination of three or more derived similitude conditions based on the known beach process relationships. One important point to note is that all of the proposed model laws satisfied the condition of the time scale being equal to the square root of the vertical scale.

Using available data, the investigators selected a tentative model law to be used in extensive verification experiments. The program was carried out the following year with the results being reported by Noda (11) in 1971. Noda conducted the experiments to determine the validity of the proposed model law, and he then proceeded to derive a completely empirical model law based on similarity of equilibrium beach profiles in the breaker zone. Unfortunately, while good representation was given in the surf zone, the corresponding dune and beach erosion was not reproduced.

The literature appears to contain no reported studies regarding model similitude relationships which were physically derived specifically for the case of dune erosion during storms. However, two studies conducted by the Delft Hydraulic Laboratory in the Netherlands provided a totally empirical model law for dune erosion (18,19). These studies derived a model law by empirical correlations of tests done at different scale dimensions when compared to a single prototype condition.

The writer's attempts to verify the Delft modeling laws using the Hurrican Eloise data proved unsuccessful. Instead of the expected massive erosion, accretion of the beach above mean sea level occurred. This result can perhaps be attributed to the fact that the Delft relationships were derived for the case of an instantaneous surge level increase above the mean sea level. When this occurs, the profile is very much out of equilibrium, and the first few waves cause a large amount of erosion to the profile. In the writer's verification attempts, the initial profile was in equilibrium, and the water level was slowly increased from mean sea level to the peak surge level, in the same manner as occurs in nature.

Similitude Considerations

Newton's Second Law can be used to show that dynamic similitude is achieved when the ratio of inertial forces between model and prototype equals the vector sums of the ratios of active forces (which are recognized as gravitational forces, viscous forces, elastic forces, surface tension forces, and pressure forces in the coastal regime). An additional requirement is that the model-to-prototype ratios of each and every force must be equal. Five of these forces are taken as independent; one (usually pressure) is determined after establishment of the others.

Since it is impossible to satisfy these requirements, except with a full-scale model, it is necessary to examine the flow situation being modeled to determine which forces contribute little or nothing to the phenomenon under study. These forces can then be neglected safely in formulating the similitude criteria with the goal of reducing the flow in an interplay of two major forces from which the pertinent similitude criterion may be theoretically developed (15).

For models of wave action and ensuing sediment transport the elastic forces, and the surface tension forces are sufficiently small that they can be neglected, provided that the water wavelength in the model is greater than about 4 in. (100 mm). Since inertial forces are always present in fluid flow, the condition for dynamic similitude reduces to equating the ratio of inertial forces to the ratio of either gravity forces or viscous forces.

For the particular case of dune erosion, the main area of interest is not the offshore zone, but the surf zone and beachface. Here the waves rush up the beach and then return down the slope, eroding or depositing sediment, or both, in their wake. During this process, particularly during severe storm conditions, the fluid particle velocities near the bed are well in excess of the critical velocity for incipient motion, and sediment is in a state of nearly constant motion. Thus, over the wave cycle, the fluid process can be idealized as unsteady, unidirectional, open channel flow up a slope followed by flow down the slope. Of course, this simplification cannot be used in an analytical approach due to the complexities involved. However, through this visualization, is is easy to recognize that the two major forces acting on a sand grain are the inertia forces, due to the turbulent flow fluctuations near the bed and the nearly horizontal component of gravity acting parallel to the beach slope. The viscous forces are small compared to the forces due to the turbulent fluctuations and, thus, can be neglected in this instance.

DYNAMIC SIMILARITY CONDITION

For convenience, it is customary to introduce the notation

$$N_a = \frac{\text{value of paramter } a \text{ in prototype}}{\text{value of parameter } a \text{ in model}} \quad \ldots\ldots\ldots\ldots (1)$$

to represent the scale ratio of a given parameter between the prototype and model. The fundamental model scale ratios can be defined as

$$\text{Horizontal Length Scale:} \quad N_\lambda = \frac{L_p}{L_m} = \frac{B_p}{B_m} \quad \ldots\ldots\ldots\ldots (2)$$

$$\text{Vertical Length Scale:} \quad N_\mu = \frac{D_p}{D_m} \quad \ldots\ldots\ldots\ldots (3)$$

$$\text{Time Scale:} \quad N_T = \frac{T_p}{T_m} \quad \ldots\ldots\ldots\ldots (4)$$

$$\text{Force Scale:} \quad K = \frac{F_p}{F_m} \quad \ldots\ldots\ldots\ldots (5)$$

in which L = horizontal length; B = horizontal width; D = vertical depth; T = time, and F = force. The subscripts p and m are for prototype and model, respectively. From these four scales, all other model scales can be derived.

Following the development of Christensen and Snyder (2), the force due to gravity in the nearly horizontal direction of the principal flow may be written as

$$F_g = \rho g \text{ (volume)}(\sin \beta) \quad \ldots\ldots\ldots\ldots (6)$$

in which ρ = the fluid density; g = the gravitational acceleration; and β = the beach slope. For small beach slopes, $\sin \beta \approx \beta \approx D/L$, so the force scale for gravity can be written as

$$K_g = \frac{\rho_p g_p \,(L_p B_p D_p)\left(\dfrac{D_p}{L_p}\right)}{\rho_m g_m \,(L_m B_m D_m)\left(\dfrac{D_m}{L_m}\right)} = \left(\frac{\rho_p}{\rho_m}\right)\left(\frac{g_p}{g_m}\right) N_\lambda N_\mu^2 \quad \ldots\ldots\ldots\ldots (7)$$

The inertial force is best represented as a horizontal or nearly horizontal area multiplied by the shear stress acting over this area, or

$$F_i = \text{area} \times \text{shear stress} \quad \ldots\ldots\ldots\ldots (8)$$

For the turbulent flow experienced next to the bed, which is in the rough range, the shear stress depends on the rate of momentum transfer and can be expressed as the Reynold's shear stress which is proportional to the fluid density and the time mean value of the product of a vertical velocity fluctuation v', and the velocity fluctuation in the direction of the time mean flow u'. Consequently, the inertial force is

$$F_i = \overline{\rho u'v'} \text{ (area)} \qquad (9)$$

and the inertial force scale ratio can be written as

$$K_i = \frac{\rho_p \left(\frac{L_p}{T_p}\right)\left(\frac{D_p}{T_p}\right)(L_p B_p)}{\rho_m \left(\frac{L_m}{T_m}\right)\left(\frac{D_m}{T_m}\right)(L_m B_m)} = \left(\frac{\rho_p}{\rho_m}\right)\frac{N_\lambda^3 N_\mu}{N_T^2} \qquad (10)$$

For dynamic similitude requiring $K_{\text{inertial}} = K_{\text{gravity}}$, and noting that $g_p = g_m$, Eqs. 7 and 10 yield the time scale, i.e.

$$N_T = \frac{N_\lambda}{(N_\mu)^{1/2}} \qquad (11)$$

Equation 11 is essentially the same as a similarity of the Froude number between prototype and model, when the Froude number is based on a vertical length and a horizontal velocity, i.e.,

$$F^* = \frac{V_{\text{horizontal}}}{(g D_{\text{vertical}})^{1/2}} \qquad (12)$$

Physically, this can be interpreted as a measure of near-horizontal displacement of a sand grain being held up just above the bed by turbulent fluctuations. The grain is moved horizontally by a velocity as it falls back to the bed vertically.

It should be noted that the derived dynamic similarity allows for a distortion between the horizontal and vertical scales. In many cases, this distortion is necessary because the reduction of size of the sand grains, as required to obtain geometric similarity, could result in sand particles so small that cohesive forces not present in the prototype would be present in the model. Use of a distorted model permits the model sediment to remain large enough to be outside the cohesive range.

Sediment Transport Similarity Condition

Besides having dynamic similarity in the model, it is necessary to find some method of determining the required distortion of the model arising from the use of natural-sized beach sand in the model. The lack of physical understanding with regard to this question has led many investigators to propose a variety of parameters to be scaled in the model, resulting in a distortion relationship (10,11). Others have used an empirical approach (18,19), as already mentioned.

Currently, a promising parameter used for the prediction of equilibrium beach slopes is the dimensionless fall velocity parameter, as presented by Dean (4), given as

$$P = \frac{H}{\omega T'} \quad (13)$$

in which H = wave height; T' = wave period; and ω = fall velocity of the sediment. Dean observed that this parameter is a good predictor of onshore-offshore sediment transport.

Dalrymple and Thompson (3) demonstrated that this parameter could be used successfully to predict the foreshore slope when H was given as the deepwater wave height. While significant scatter was present in the data representation, they reported a much better correlation then when the same data were plotted vs. H_0/L_0 and a third parameter pertaining to grain size. They concluded that the parameter $H_0/\omega T'$ should be preserved between the model and the prototype in order to reproduce the same equilibrium profile.

Noda (12) investigated both full-scale and small-scale model results for profile similarly and found that a much closer similarity could be obtained when the $H/\omega T'$ parameter was conserved than when wave steepness, H_0/L_0, was held constant. He also offered an empirical relationship for the selection of model grain-sizes and concluded that movable-bed coastal models could be distorted, but the validity still needed to be confirmed.

Based on this growing amount of evidence, it becomes increasingly clear that the parameter $H/\omega T'$ should be the same in the model as in the prototype for profile similarity. This will also allow the sediment grain size and specific weight to be incorporated into the model law as a single variable, ω. This requirement becomes

$$\frac{H_p}{\omega_p T'_p} = \frac{H_m}{\omega_m T'_m} \quad (14)$$

$$\text{or} \quad N_T = \frac{N_\mu}{N_\omega} \quad \text{in which} \quad N_\omega = \frac{\omega_p}{\omega_m} \quad (15)$$

Dune Erosion Model Law

Since the time scale for wave motion is the same as the time scale for the resulting turbulent velocity fluctuations, Eq. 15 can be equated to the dynamic similarity criterion of Eq. 11, yielding

$$N_\lambda = \frac{N_\mu^{3/2}}{N_\omega} \quad (16)$$

Equations 11 and 16 provide the complete requirements for scale-model testing of dune erosion during storms using a movable-bed model. Actually these equations should fulfill the modeling requirements for the determination of any profile alterations due to wave action in the surf zone, not just those due to storm conditions.

Morphological Time Scale

Making the morphological time scale the same as the hydraulic time scale will conserve the number of incoming waves per unit time, thus, conserving the incoming wave energy per unit time, and this seems most plausible, in view of the scaling of the particle fall velocity and the length scale distortion. The time scaling of the surge duration should also be to the same scale.

Unfortunately, not enough is known about beach process reaction times to determine the morphological time scaling unequivocally. However, results from Saville (16) indicate that better time-dependent profile comparisons are given if the time scale is distorted.

It is easily seen that the proposed time scaling given by Eq. 11 can be expressed as

$$N_T = \Omega N_\mu^{1/2} \quad \text{(17)}$$

$$\text{in which} \quad \Omega = \frac{N_\lambda}{N_\mu} = \text{model distortion} \quad \text{(18)}$$

Thus, the time scale has the same distortion as the lengths in the model. If the model distortion is increased, the beach process will occur in a shorter time in the model. Thus, the assumed morphological time scaling is in basic agreement with Saville's observations.

While the aforementioned reasoning appears to be qualitatively correct, a further confirmation of the morphological time scale for beach processes is needed. However, the results of the model verification, examined later, indicate that the assumed time scaling is quite reasonable.

Examination of the Model Law

The two equations given, Eq. 11 and Eq. 16, are expressed in terms of four variables, N_λ, N_μ, N_T, and N_ω. This allows the experimenter the freedom of selecting two of the scaling ratios to suit the model facility.

The main difference between this model law and previous attempts is the derived time-scale relationship. The other model laws have expressed, for the most part, the time scaling as

$$N_T = N_\mu^{1/2} \quad \text{(19)}$$

which usually arises as a result of trying to preserve the wave steepness parameter H_o/L_o.

In contrast, this proposed model law preserves the dimensionless fall velocity parameter, which has been shown to be a better indicator of beach processes. This results in a distorted time scale given by Eq. 17. One drawback that might arise from this distortion is that the reflection of the incipient waves may become significantly greater in the model than in the prototype, and care must be taken to minimize this effect by selection of scales which give a small distortion.

It is interesting to note that Eq. 16 is identical to the empirically derived distortion given by Vellinga (19) for fine sand, and the only difference between the model laws is the time scale [Eq. 19 as compared to Eq. 17].

It is possible to have an undistorted model, using these proposed relationships, by the proper selection of sediment for the model. This represents the ideal condition, as long as the resulting model sediment size is still outside the cohesive sediment range. Using Eqs. 11 and 16 with $N_\lambda = N_\mu$, the requirement becomes

$$N_\omega = N_\mu^{1/2} = N_T \qquad (20)$$

Note that in this special case of an undistorted model, the time scaling reduces to that given by Eq. 19; thus, the parameter H_o/L_o, as well as $H/\omega T$, is being conserved. However, this condition is quite often impossible to satisfy due to the fairly large length scale ratio, N_μ, is required to model typical sandy beaches. Sometimes choosing a lighter material to use as the sediment in the model will result in an undistorted model, but this is often expensive and difficult.

It is interesting to note that Battjes' (1) surf similarity parameter, given as

$$\xi = \frac{\tan \beta}{\left(\frac{H}{L_o}\right)^{1/2}} \qquad (21)$$

is preserved by the proposed model law. Representing $\tan \beta = D/L$, and $L_o = g/2\pi\, T^2$, then

$$\frac{\xi_p}{\xi_m} = \frac{\frac{D_p}{L_p}\left(\frac{g_p}{2\pi}\right)^{1/2}\frac{T_p}{H_p^{1/2}}}{\frac{D_m}{L_m}\left(\frac{g_m}{2\pi}\right)^{1/2}\frac{T_m}{H_m^{1/2}}} = \frac{N_T N_\mu^{1/2}}{N_\lambda} \qquad (22)$$

when $(g_p/g_m) = 1$.

Substitution of Eq. 11 for N_T yields

$$\frac{\xi_p}{\xi_m} = \frac{N_\lambda}{N_\mu^{1/2}} \cdot \frac{N_\mu^{1/2}}{N_\lambda} = 1 \qquad (23)$$

Thus, similarities that Battjes noted were related to the similarity parameter should be successfully scaled using the proposed model law.

Model Verification

Complete verification of a movable-bed scale-model is perhaps the most difficult task in the whole realm of modeling. The main principle behind verification is that of being able to reproduce in the model the results of a prototype event by the scaling of the known parameters of the event. In the case of dune erosion, the assumption is made that the process is strictly that of onshore-offshore sediment movement. While perhaps not totally correct, the general feeling among many investigators is that onshore-offshore motion is the primary mechanism at work during storms; thus, the process can be successfully modeled in two dimensions with the hope that the other effects are small.

There are three major characteristics of dune erosion which must be reproduced in the model test in order to satisfactorily obtain verification:

1. For the correctly scaled input parameters determined for the prototype, the total volume of dune material eroded above mean sea level in the model must approximate the same volume eroded in the proto-

type when the proper scale factors are applied.

2. This erosion must occur over the time span of the surge duration as scaled in the model.

3. The poststorm foreshore beach slope must duplicate that which existed in the prototype when the distortion factor is applied. By doing this, the derived distortion of the model is verified.

Selection of Prototype Conditions.—The prototype event selected for reproduction in the small-scale model was that of Hurricane Eloise, which struck the Florida Panhandle in September, 1975. This storm eroded large sections of relatively undeveloped natural dunes.

Under the Florida Coastal Construction Setback Line Program (14), the coastal areas primarily affected by Hurricane Eloise were surveyed about two years before. Immediately after the passage of Eloise, survey teams from the Florida Department of Natural Resources resurveyed the profiles in the areas most affected by the storm. From this data set, a representative beach profile, located almost exactly on the track of the hurricane's eye, was selected for the model tests. The profile had a 26-ft (8-m) high dune, and sand samples taken in the immediate vicinity of the profile were available for analysis. A composite analysis of the available sand samples from the beach and dune provided a representative effective mean grain-size diameter of $d_e = 0.262$ mm.

The value of peak storm surge was estimated to be slightly over 8 ft (2.4 m). This estimate was based on examination of the eroded profile, application of the nomogram method provided in the Shore Protection Manual (17), and a computer prediction for Hurricane Eloise given by Pidgeon and Pidgeon (13).

The time history of the surge level rise in the prototype was approximated as a linear increase from mean sea level to peak surge level over a time span of 12 hr, a constant peak surge level for 1 hr, and a linear decrease over 6 hr. This was determined by examining the recorded surge time histories associated with storms of similar strengths as Eloise.

Since no near-shore wave data exist near the chosen site, estimates of the significant wave height and the modal wave period were made using data recorded on the Naval Coastal System Laboratory tower located 11 mile (18 km) offshore from Panama city, Florida. For the selected profile, the modal wave period was estimated to be 11 seconds while the significant wave height was approx as 12 ft (3.7 m).

Of the estimated storm conditions, the peak storm surge is probably the most accurate, and the estimated significant wave height is least accurate. However, the model series which followed the verification tests indicates that variations in the wave height and wave period have a much lesser effect on the dune erosion than do variations in peak storm surge. A more detailed explanation of the wave climate estimates is given by Hughes and Chiu (8).

Model Scale Selection.—The sand selected for use in the small-scale model verification had an effective mean grain-size diam of 0.147 mm. This was achieved by removing all grain sizes greater than 0.3 mm in diam. The resulting narrow grain size distribution compared favorably with that of the prototype, one being nearly a linear offset of the other. The resulting grain-size fall velocity scale was found to be $N_\omega = 2.424$.

By selecting the vertical scale ratio as $N_\mu = 25$, which best suited the wave facility, Eqs. 11 and 16 provided the following scaling factors: Vertical length scale, $N_\mu = 25$; Horizontal length scale, $N_\lambda = 51.56$; Time scale, $N_T = 10.31$; and Model distortion, $\Omega = 2.06$.

Wave Flume Facility.—The model verification was conducted in a two-dimensional wave flume at the Coastal and Oceanographic Engineering Laboratory at the University of Florida. A full description of the test facility and procedures is given by Hughes and Chiu (8); but, briefly, the flume is 120 ft (37 m) long, 34 in. (860 mm) wide, and had an initial water depth of 18 in. (460 mm). The time-dependent surge level increase was controlled by a calibrated water inlet valve emptying into the wave flume stilling basin. The input water volumetric flow, as required to model the surge hydrograph, was never of sufficient magnitude to generate a current flow in the flume. Waves were generated by an electronically controlled, hydraulically driven wave paddle with an upper and lower ram. The paddle motion consisted of a piston motion combined with a paddle motion about the bottom of the wave paddle.

Early Attempts at Verification.—The first attempts to verify a model law were carried out using the scaling relationships proposed by Vellinga (19). In tests using both monochromatic and irregular wave trains, sediment was moved from offshore and deposited on the beach as the surge level increased. This lead to the development of the scaling relationships presented in this paper.

Following establishment of the model law, over 16 attempts were made at model verification using an irregular wave field. None of these runs produced results which satisfactorily fulfilled the requirements for verification. An example is shown in Fig. 1.

As can be seen, the amount of dune recession is good, and the resultant beach slope is nearly right; the recurring problem was that the erosion was not deep enough, and the sand was not being transported offshore far enough.

Perturbations of each of the input parameters were made to see if the estimation of one of the storm parameters was inaccurate. None of these variations produced the desired result. After looking at possible causes, from wave reflection to paddle response to spectral representations and so forth, it was finally decided that the problem was in trying to use irregular waves in the model. One of the main characteristics of shallow-water wave spectra is the presence of phase grouping, which is a function of both space and time. While the random time series generated for use in this model verification attempt conformed to the desired statistical representation, there are an infinite number of different time series which will also conform, none of which depict the wave groupiness present in shallow-water random wave fields before breaking. This probably was the cause of the failure to verify the model when spectral wave distributions were employed. This view is also supported in the reviewer's comments presented in a report by Jain and Kennedy (9), where the statement is made that small-scale movable-bed modeling should be restricted to regular waves until more is known about near-shore random wave phenomena.

Additionally, it has been shown that the generation of random waves in model facilities has the tendency of generating long "parasitic" waves

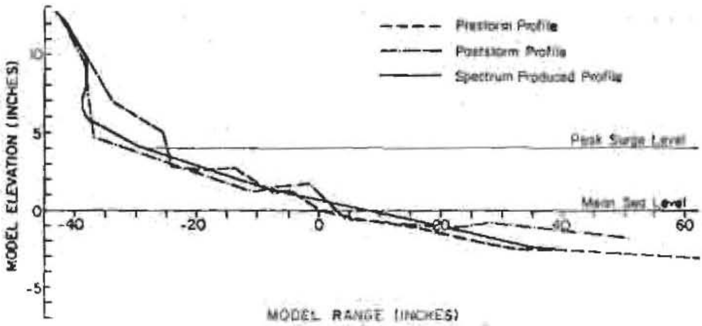

FIG. 1.—Attempted Model Verification Using Wave Spectrum (1 In. = 25.4 mm)

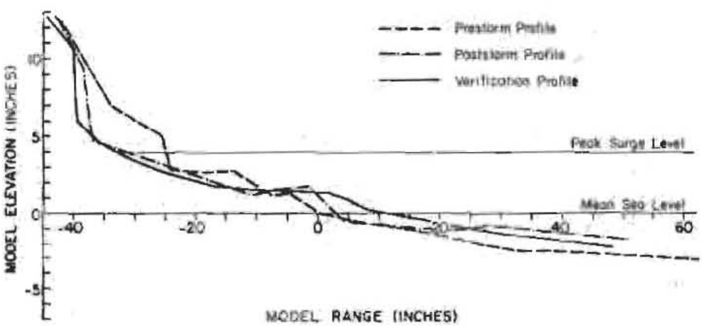

FIG. 2.—First Model Verification Run, Final Profile on Centerline (1 In. = 25.4 mm)

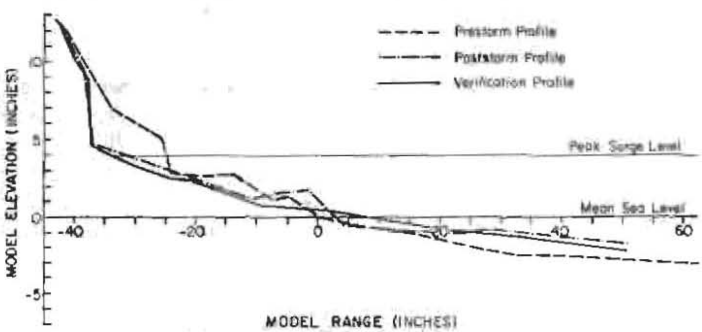

FIG. 3.—Second Model Verification Run, Final Profile on Center Line (1 In. = 25.4 mm)

(6). This fact was observed in the verification process on a strip chart recording of a random wave train, which illustrated a parasitic long wave with a period between 15 sec and 20 sec. This low frequency energy was not present in the prototype, and attempts to filter out these long wave components were unsatisfactory. For the aforementioned reasons, it was decided that the model verification and ensuing experimental test series be conducted using monochromatic wave trains.

Verification Tests Using Monochromatic Waves.—Two documented verification runs were performed using regular waves and reproducing nearly the same storm conditions. The second run was required in order to demonstrate that the results of the first run could be reproduced, and because a slight wave period variation was observed near the end of the first run.

The parameters for the first run are given in Table 1 with both model and prototype values shown. The surge increase was approximately linear over the time span, and the wave period was held constant throughout. The prototype wave height of 8.5 ft (2.6 m) gave the same wave energy density as a narrow-band spectrum with a significant wave height of about 12 ft (3.7 m); while the surge level was on the increase, the wave height was gradually increased in a stepwise manner until the peak value was reached at 38 min into the run, or about when the surge was half its peak value. This value was maintained until the surge level began to decrease at which time the wave height was again reduced. This process should be reasonably representative of the prototype wave height variation during passage of the storm.

Figure 2 shows the measured profile along the center line of the wave flume at the end of the verification run. Profiles measured near the glass wall and the back wall indicated that there was a slight lateral variation in the eroded profile. However, the erosion which occurred compared very favorably with the prototype, with the exception of the extra dune recession.

A standard post-test check of the wave data revealed that the wave period was inadvertently increased slightly during the latter 3 min of the peak surge duration. It is assumed that this increased wave period

TABLE 1.—First Verification Run Parameters

(1)	Wave period, in seconds (2)	Maximum wave height (3)	Peak surge level (4)	Time to reach peak surge (5)	Time at peak surge (6)	Time of surge decrease (7)
Prototype value	11.0	8.5 ft (2.6 m)	8.3 ft (2.5 m)	12.4 hr	1.9 hr	5.2 hr
Model value	1.07	4.1 in. (104 mm)	4.0 in. (102 mm)	72 min	11 min	30 min

TABLE 2.—Second Verification Run Parameters

(1)	Wave period, in seconds (2)	Maximum wave height (3)	Peak surge level (4)	Time to reach peak surge (5)	Time at peak surge (6)	Time of surge decrease (7)
Prototype value	11.0	8.5 ft (2.6 m)	8.3 ft (2.5 m)	12 hr	1.4 hr	5.2 hr
Model value	1.07	4.1 in. (104 mm)	4.0 in. (102 mm)	70 min	8 min	30 min

(equivalent to 13 sec in the prototype) was the cause of the extra dune recession.

Table 2 gives the storm parameters for the second verification run which proceeded in much the same manner as the first run. As before, the surge rise was approximately linear with the wave period being held constant throughout. The wave height was gradually increased to its peak value which occurred at about 48 min into the run, and the wave height was decreased as the surge level dropped, signifying the passage of the storm.

This run showed little discernible lateral variation in the eroded profile; the eroded quantity and dune recession gave a very credible reproduction of the prototype event, as can be seen in Fig. 3, which gives the post-test profile measured on the flume center line. Near the glass, the profile was slightly elevated.

Examination of Model Verification.—Verification of the proposed model law seems to have been successful based upon the previously mentioned results. Estimation of the storm parameters was deemed to be as reasonable as possible in view of the limited data available. Eroded profiles obtained during model testing closely resemble the prototype profile in terms of recession, eroded volume, and beachface slope. As can be seen on Figs. 2 and 3, reproduction of the poststorm beach berm (between model range -10 and $+5$) was not achieved. However, this berm feature was formed by low-steepness swell wave conditions which occurred between the passing of Hurricane Eloise and the measurement of the profile several days later; thus, reproduction of the berm was not expected in the model tests. The region above the berm elevation was not effected by the poststorm waves.

Several observations that provide some basic insight into the erosion process were made during the verification:

1. As the surge level began to rise, there was little change in the profile until the latter stages of the increase when more of the dune was exposed to the erosive wave action. This indicates that surge level is an important parameter in the erosion process.
2. The erosion that had occurred by the time the peak surge had been reached represented between 80%–90% of the final erosion quantity. Thus, it is seen that the most damage is done during the surge rise and the time the surge remains at its peak value.
3. As the surge level was lowered and the wave energy decreased, the profile was not changed appreciably. The most noticeable effect as the water level decreased was a smoothing of the profile. This was caused by the deposition of sediment over the beachface and the transition from plunging breakers to spilling breakers.

Applications and Recommendations

The movable-bed similitude relationship presented in this paper may be used to model two-dimensional beach processes under the following assumptions:

1. Natural, sandy, straight beaches with relatively uniform offshore depth contours.

2. No interactions with tidal inlets or coastal structures.
3. Onshore-offshore sediment transport with no alongshore currents.
4. No dune overtopping.

Further research is needed to confirm the existance of profile similarity between models of different scales and different grain sizes. Tests should also be conducted to determine how small the model can be made before scale effects begin to dominate the processes. Verification of prototype events should be attempted whenever accurate prototype data become available. This would further enhance the reliability of the model law and give a more complete understanding of the scaling effects. When it becomes practical to use wave spectra in a movable-bed model, then they must be employed.

SUMMARY AND CONCLUSIONS

Movable-bed small-scale modeling of coastal erosion has been historically an inexact science. The modeling relationships developed herein were derived through the consideration of the inertial forces, represented by the turbulent shear stress and the gravity force in the nearly horizontal direction of the principal flow. This resulted in a dynamic scaling relationship for a distorted model. The profile similarity criterion was based on the preservation of the dimensionless fall velocity parameter, which has been shown to be an important factor. Combining these two criteria resulted in a model law similar to previous results, differing primarily in the hydrological time scaling. By proper selection of model grain size, it is possible to have an undistorted model, which is the ideal case, but often not possible for small prototype grain sizes.

Verification of the derived modeling relationships was achieved by a wave tank simulation of dune erosion from Hurricane Eloise. Storm parameters were estimated as closely as possible from the limited data available. Use of these storm parameters for the laboratory simulation resulted in a reasonable reproduction of the prototype erosion experienced during Hurricane Eloise. The verification procedure gains additional credibility by virtue of the simulation of the time-dependent storm surge hydrograph, increasing the model wave height up to the peak surge level and decreasing the model wave height as the surge level decreased. To the writer's knowledge, this was the first time that these dynamic features had been incorporated into the verification of a movable-bed model of dune erosion.

Attempts to verify the model using a randomly produced irregular wave train, fitting the spectral requirements, proved unsuccessful due to the absence of phase grouping, and the presence of low frequency energy brought about by laboratory "parasitic" wave generation.

It is concluded that the model verification has been successful in, at least, one instance for which prototype data were available. There is certainly a need for additional verification; however, this must either await additional prototype data or must include highly variable laboratory scale experiments. Until such time, the derived movable-bed modeling relations presented in this paper represent a plausible means of investigating beach-dune erosion in a physical model. It is hoped that further research will add greater confidence to the modeling relationship and, thus, pave the way for routine quantitative physical modeling of coastal processes.

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Appendix II.—Notation

The following symbols are used in this paper:

B = horizontal width dimension;
D = vertical dimension;
F = force;
F_g = force due to gravity in nearly horizontal direction of principal flow;
F_i = inertial force;
F^* = Froude number based on a vertical length and a horizontal velocity;
g = acceleration of gravity;
H = water wave height;
H_o = deepwater wave height;
K = force scale (ratio of force in prototype to force in model);
K_g = force scale ratio for force due to gravity;
K_i = force scale ratio for force due to inertia;
L = horizontal length dimension;
L_o = deep-water wavelength;
N_a = scale ratio of a in prototype to a in model;
N_T = scale ratio of time in prototype to time in model;
N_λ = scale ratio of horizontal length in prototype to horizontal length in model;
N_μ = scale ratio of vertical length in prototype to vertical length in model;
N_ω = scale ratio of sediment fall velocity in prototype to sediment fall velocity in model;
P = dimensionless fall velocity parameter ($H/\omega T'$);
T = time;
T' = water wave period;
u' = turbulent horizontal water velocity fluctuation;
v' = turbulent vertical water velocity fluctuation;
β = beach slope;
ξ = surf similarity parameter;
π = mathematical pi (3.14159....);
ρ = fluid density;
Ω = model distortion = N_λ/N_μ; and
ω = sediment fall velocity.

Subscripts

m = model value; and
p = prototype value.